REACTIVE POWER COMPENSATION FOR INDUCTION GENERATOR

by

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May, 1999

CERTIFICATE

This is to certify that the work contained in this thesis entitled "Reactive Power Compensation of Induction Generator", by Anirban Chakraborti, has been carried out under my supervision. This work is not submitted elsewhere for any other degree.

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April, 1999

DEDICATED TO MY PARENTS

Acknowledgment

It is a privilege to work under the guidance of Dr. G. K. Dubey, who has always motivated me to think with audacity and create humbly with perseverance. His exceptional capability of reducing complexities to simpler form has enormously helped in the smooth progress in the work. He has been extremely enthusiastic and patient while attending to my work. It is an enlightening experience to learn and create under his caring attitude. With sincerity and honesty I express my profound sense of gratitude and indebtedness to my teacher and supervisor.

The simulating and informal atmosphere of the Department of Electrical Engineering at I. I. T, Kanpur has been a great help for me. It has been a great pleasure to learn and study in association with Professors S. P. Das, S. R. Doradla, A. Joshi and others.

With a great sense of gratitude, I acknowledge here the inhibited cooperation and motivation of Dr. K. Chattergee.

It would have been impossible to venture into this work without the active support, encouragement and inspiration from my parents. I must mention that my strongly anchored root at my home has always stood by me at the hour of need.

April, 1999 Anirban Chakraborti

ABSTRACT

Traditional method of Static Reactive Power compensation for Self-Excited Induction Generator based on Switched Capacitor or Fixed Capacitor and Thyristor controlled reactor are increasingly being replaced by new approaches utilizing the concept of Synchronous Link Converters. The two main advantages for which this class of reactive power compensation schemes have drawn tremendous interest from the researchers and power regulating authorities, are- 1) considerable reduction in ac passive elements thereby reducing size, losses and projected cost, and 2) near constant reactive power generation capability (both leading and lagging) even during low voltage condition. Moreover, as these type of compensators can be realized by self-commutated devices, better controllability over switching non-linearity is ascertained. Hence harmonics generated by this compensators remain low.

A new control scheme for SEIG with controlled current SLCVC is taken up as the first investigating object of the dissertation. The present scheme is realized by a simple control structure thereby enhancing the system reliability. The scheme has a SLCVC in parallel with a fixed valued capacitor bank. The fixed valued capacitor bank is used for starting SEIG. It also supplies the reactive power, which is the average of the reactive powers needed at full load and at reduced load. The mathematical model for the scheme is developed. The validity of the scheme is verified through extensive simulation.

Attempts are also made to analyze the steady-state performance of SEIG both in three-phase and single-phase case. Conventionally two analysis techniques are used. They are 1) Loop impedance method, and 2) Node admittance method. In this dissertation Loop impedance method is used. Capacitive reactive power required by an Induction generator is also determined to facilitate the design of the close-loop control scheme and to calculate the value of the capacitor bank needed for the closed loop scheme. A design technique has been provided for the Voltage-source Converter.

Thus in this dissertation a consolidated effort is made to develop a reactive power compensation scheme with power-electronic interface. The viability of the proposed scheme can be confirmed through experimental studies.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Electrification, in rural areas and remote locations is considered an important task for the balanced development of a country as the electric energy has become a basic need of human society for living a normal life today. The grid-power has often become inadequate or not available to several areas mainly those in remote and inaccessible locations. Traditionally, synchronous generators with fossil-fuels such as diesel have been used for power generation in remote areas. The growing concern for environment, the increasing cost for rapidly depleting fossil fuels and techno-economic difficulties in extending existing power grid in remote locations, have led to increased use of locally available energy resources. The naturally recycled resources such as wind, hydro, solar, bio-energy are perennial and hence need to be utilized to meet the growing energy demand. Development of appropriate energy conversion system in low power ranges to feed energy to local feeder by harnessing these renewable resources of energy, have taken a considerable significance. Electric power generating system for such

applications should be simple, economical, maintenance free and capable of operating with variable speed condition. These requirements have renewed the research on technology of electric power generator, other than conventional alternator at least in low power range as the latter is found to have high cost, require frequent maintenance due to the brushes and unsuitable for variable speed prime mover. For such applications, the induction machines are being favored due to their overall operational advantages and maintenance simplicity.

While the operation of induction machine as a motor is well known, its operation as a generator is drawing considerable attention from researcher and engineers due to some of its versatile qualities. In isolated applications, an induction machine driven by a prime mover operates as a self-excited induction generator (SEIG) with its excitation requirements being met by capacitor bank connected across its terminals. The resultant SEIG systems use conventional resources of energy (viz. Hydro, Diesel, Gas etc.) and/or non-conventional resources of energy (viz. Wind, Biogas, Wave etc.). The use of self excited induction generator as a source of isolated power supply in wind-mills and microhydro power plants is very popular.

1.2 Advantages

Induction generators are capable of generating power from variable speed as well as constant speed prime movers such as wind turbines, microhydro turbine, gas turbine, diesel and bio-gas engines.

Cage induction machines, in particular, are rugged in construction and have low cost ($20/kw compared to $50/kw in synchronous generator) and easy availability even at lower speed. Induction generators do not need a separate DC exciter and other equipment such as field breaker and synchronization circuit. Therefore they have operational and maintenance simplicity. The protection of the machine is simple and cheap because the fault current level of the machine collapses to zero as the capacitor excitation falls with terminal voltage. Due to slip action in an induction machine, the problem of hunting due to synchronization torque does not appear when two or more induction generators at different speeds are connected in parallel. The rotor is brushless and there is no moving contact. The transient impedance is very low and it offers potential improvements in power system dynamic performance.

The single-phase as well as three-phase SEIG have become popular for small scale power generation typically in the range of 0.5 kw to 250 kw. They are used for feeding individual as well as group loads in situations like a remotely located village community or hamlet, a military post, a hospital, a microwave station, and project and construction sites. Depending upon the size of the load, SEIG configuration changes. As a community develops, demand of electricity grows such that different schemes of single-phase and three-phase power generation and distribution are required at different stages of development. Single-phase supply is suitable up to a load of 20 kw in view of cost effectiveness of the distribution system. The three-phase supply on the other hand, is preferred to feed the load of more than 20 kw. Since the single-phase induction machines are generally not

available in the integral kw rating higher than 5 kw, single-phase power supply using single-phase SEIG is restricted up to the load of this capacity. So, for a load of more than 5 kw, three-phase generators are used. A multiple number of three-phase SEIGs are operated in parallel when there is further increase of load.

1.3 Disadvantages

In spite of all the advantages there is a big disadvantage which forbids the use of induction generator in many a case. The output voltage of induction generator is very sensitive to the speed and load fluctuations. An increased speed can cause severe over voltage causing stress on the insulation and affecting the load connected to the induction generator. A low speed causes the voltage to fall very fast. The machine loses its excitation when the speed falls below the critical level. Similar things happen in case of load fluctuations. When the load current demand goes up, the voltage regulation becomes poor (as most of the loads are inductive and resistive asking for more excitation). A sudden load cut off causes both the voltage and speed to shoot up endangering both the mechanical parts and electrical insulation. The main cause of all these problems is the VAR consumption by the magnetizing reactance. The only way to tackle this problem is to change the excitation current to the induction generator as we do not have any hold either on the speed (determined by wind velocity or water head as the case may be) or on the load fluctuations (governed by consumer demand).

1.4Prospects of Induction Generator in India

The main application of induction generator in India is presently in the field of grid-connected wind farms. India occupies third place in wind electricity generation, having an installed capacity of more than 800MW. Influenced by the growth of Californian wind-farms and influenced by the Danish industry, the department of non-conventional energy in India planned and set up wind-farms with induction generators in Gujarat and Tamilnadu, where the wind conditions appeared most favorable. Numerous private wind-farms came up at Muppandal, Kayathar and Kethanur in Tamilnadu. The relative growth was low in Gujarat. However, eight states of the country have grid-connected electricity generation today. As it happens the growth rate declined when the initial enthusiasm withered away. Moreover, the reactive power required for the magnetization of the induction generator, has to be supplied by the connected grid. VAR drain due wind electric generator, has forced utility operators in India to impose a penalty on reactive power consumption in of wind farms, which in turn caused considerable disillusionment among the latter. The capacity at the end of 1996 in various countries is as (IREDA news):

Table.1.1

Country	Wind Power Capacity(1996),MW
USA	1650
Germany	1545
India	816
Denmark	733

1.5 Principle of self excitation

Self-excitation on an externally driven induction machine begins by the action of either a residual flux or charge on excitation capacitor. This residual flux linkage with the rotation of rotor develops an induced voltage in the stator windings, which causes a small excitation current flowing in the winding. The m.m.f produced by the excitation current strengthens the air-gap flux in the presence of the excitation capacitor and helps further to develop the generated voltage. With the sufficient capacitance, the process of voltage build-up continues until it settles to a steady state operating point determined by the magnetization characteristic of the machine, speed of the rotor and the excitation capacitance. For a fixed capacitor bank there exists a speed called critical speed below which there is no self-excitation. Similarly for a given speed there exists a critical value of capacitance below which no voltage build-up is possible.

The reliability of starting can be made high by one of the four following methods :

1.By passing a DC current through the machine before it is run up to rated speed, certain residual magnetism is guaranteed.
2.By switching in charged terminal capacitors. It can be charged at rated machine voltage.

3.By increasing the machine speed over rated value.

4.By adding a terminal capacitance so as to reduce critical speed.

1.6Traditional Methods of Var Compensation

Conventional methods of reactive power compensation rely on the var generated or absorbed by the passive elements having energy storage capability. Dynamic compensation is achieved by either connecting these elements in steps as in switched capacitor var compensators or by applying variable voltage to these elements by using anti-parallel thyristorised voltage controllers as in Thyristor Controlled Reactor. Since the reactive power generated or absorbed is directly proportional to the energy storage capability of the passive elements, there is a considerable increase in size of the elements with the increment in reactive power to be compensated. The introduction of sizable inductors and capacitors in SEIG system may lead to resonance created by peripheral low frequency current sources. Moreover, the capability of this class of compensators to manipulate reactive power depends on the voltage level prevailing at the point to which it is connected. Since the bus voltage reduces as the reactive power demand increases these compensators fail to perform when their participation is most needed. Some of these pollute the SEIG system with the low order harmonics which are difficult to filter. Moreover, with supply frequency change and aging of passive elements, the compensator gets de-tuned deteriorating compensator efficacy.

1.7Modern Var Compensators

The basic philosophy of this class of compensators is to use the non-linear characteristics of power electronic switching in var generation. In theory, as no energy storage passive elements are required, there is a significant reduction in size and projected cost of this kind of compensator. This results in low system losses and higher efficiency.

The second very important advantage of these compensators is that their reactive power generating capability is independent of the magnitude of the voltage prevailing at the point to where they are connected. Further, they provide better flexibility in reactive power management. These compensators are commonly known as STATCOM, SLCVC, STATCON, Synchronous Solid State Var Compensator etc.

1.8Objective of the Work

Since controlled current SLCVC provides almost a sinusoidal compensating current, their performance characteristics are superior compared to other control schemes. The response time of these compensators is around 2-3 power cycles. A SEIG requires an excitation source that is capable of releasing or absorbing the reactive current in

order to regulate the terminal voltage with changing load under steady-state and transient conditions. A new scheme for reactive volt-ampere valid for three-phase systems is proposed. This proposal serves as the first investigative object of the dissertation. A mathematical model for the scheme is developed and detailed simulation studies for three-phase topology are presented.

Attempts are also made to analyze the steady-state performance of SEIG both in three-phase and single-phase case. Capacitive reactive power required by an Induction generator is also determined to facilitate the design of the close-loop control scheme. A design technique has been provided for the Voltage-source Converter.

1.9 Organization of the Thesis

The work presented in this dissertation is organized as given below.

A review of reactive power compensation schemes and analysis techniques are reported in the literature review presented in chapter 2. Merits and demerits of the available schemes are also examined.

In chapter 3, an attempt has been made for the determination of capacitive reactive power required by an Induction generator. Different performances are also analyzed in the chapter.

Chapter 4 explores the use of SLCVC for close loop control of terminal voltage of an SEIG at varying load conditions. To start with,

theoretical generation of controllable reactive power using a voltage source inverter is briefly reviewed. The principle of operation of SLCVC and control approach for regulating the terminal voltage of SEIG is described. The d-q axes model in stationary reference frame, which is widely used for the analysis of induction machine is used for simulating the effectiveness of the SLCVC based voltage regulator for controlled supply of excitation current required for controlling the terminal voltage of SEIG in synchronism with load.

An attempt is made in chapter 5 to analyze the steady-state performance of capacitor self-excited single-phase induction generator. An analytical technique is used to determine the excitation requirement to maintain the voltage at desired level at a desired speed. The technique uses a standard equivalent circuit to obtain non-linear algebraic equations in terms of unknown parameters and the Newton-Raphson method is used to solve them. Different effects are also studied on generator performance, which would provide the proper guidelines for the design of a regulating and converting systems.

Chapter 6 presents design procedure for VSC, which use MOSFET as switching devices, thus making use of their high switching frequency capabilities. The design is done for a single-phase half-bridge VSC. A design procedure along with appropriate considerations for the selection of the converter elements is hence presented.

Chapter 7 summarizes the conclusions of the work and gives suggestions for further research in the field.

Chapter 2

Literature Review

2.1 General

The possibility of operating induction machine as self-excited Induction generator was demonstrated in the decade of nineteen thirties by E.D.Basset, C.F.Wagner and E.M.Potter. The basic theory of induction generator (first made by B.C.Doxey), few cases of its application such as in aircraft system, and static excitation of induction machines [1-3] to operate as generator were reported by the turn of decade of seventies. The importance of the renewable energy such as wind, hydro, tidal, solar and biomass as the alternative to fast depleting fossil fuels was realized after the oil crisis of seventies.

2.2 VAR compensation topologies

The inherent poor voltage regulation of the SEIG is identified as a major bottleneck in its application to isolated applications. The generated voltage of SEIG can be controlled by either adjusting the level of excitation current or by adjusting the turbine speed. Adjustment of speed is not possible in all the prime movers and it requires complicated control of prime mover. Therefore, the supply of excitation current is adjusted by changing the capacitive var with the load in such a way so that the terminal voltage remains constant. Voltage regulators are used for this purpose. Efforts have been made by researchers to tackle this problem [2, 4-16].

Doxey has proposed a means of regulating the voltage with the help of suitably matched star-delta saturable reactors, further improvements being obtained by converting the reactors to magnetic amplifiers by adding DC winding, fed by a suitable voltage regulator. This method, however, is costly; not only due to the cost of the inductor required, but also they must be matching with a particular machine used. Ooi and David [17] have applied synchronous condenser for regulating the voltage of induction generator. The added cost and maintenance requirement of synchronous condenser, however, overrides the advantages of induction generator.

Switched capacitor scheme is another method that has been applied to regulate the SEIG voltage if the variation of terminal voltage in a specified limit is permitted [4, 5, 10]. The method controls the voltage in steps. The control of voltage of SEIG terminal is achieved by a static var compensator (SVC) which is realized through a fixed valued capacitor bank in parallel with thyristor controlled inductors [5]. The fixed capacitors are selected to provide the maximum reactive power needed by the induction generator, and switched inductors are controlled by thyristor in such a way so that the excess reactive power, which is not needed by the generator, can be absorbed by it. However, such SVC excitation has a problem of harmonic injection, decrease of var output with square of voltage, loss in the inductor and large system requiring a number of major components.

Singh et al. [11] has explored an alternative method of regulating the SEIG terminal voltage by using saturable core reactor. In this method, the fixed capacitor is selected to such a value that it meets the no-load excitation current of the SEIG and SCR. However, it looses the control below a certain voltage range and also involves high copper loss. Also, this type of regulator involves large size and weight due to the necessity of large inductors. The long shunt and short shunt configurations of SEIG proposed separately by Bim et al [12] and Shreedhar et al [18] provide the self-regulation of the voltage of the SEIG system by connecting capacitors in series with the load. Some of the var compensating schemes are provided in Fig.2.1. Mujaldi and Lipo [15] have proposed a series compensation scheme of SEIG utilizing a PWM inverter in order to control the excitation and real current flow. The scheme involves the complexity due to requirement of DC source (Fig.2.2).

Recent advancement in the semiconductor devices, power converters and control circuits have resulted in a solid-state source of var having fundamentally different operations and functional characteristics than those obtained previously with conventional SVCs. Chatterjee [19] has used a voltage source inverter called SLCVC or STATCOM to control reactive power in a load. The review of STATCOM related literature reveals that STATCOM may be used as variable reactive power source but no attempt has yet been made on utilization of the STATCOM for the voltage control of the SEIG in autonomous power generation.

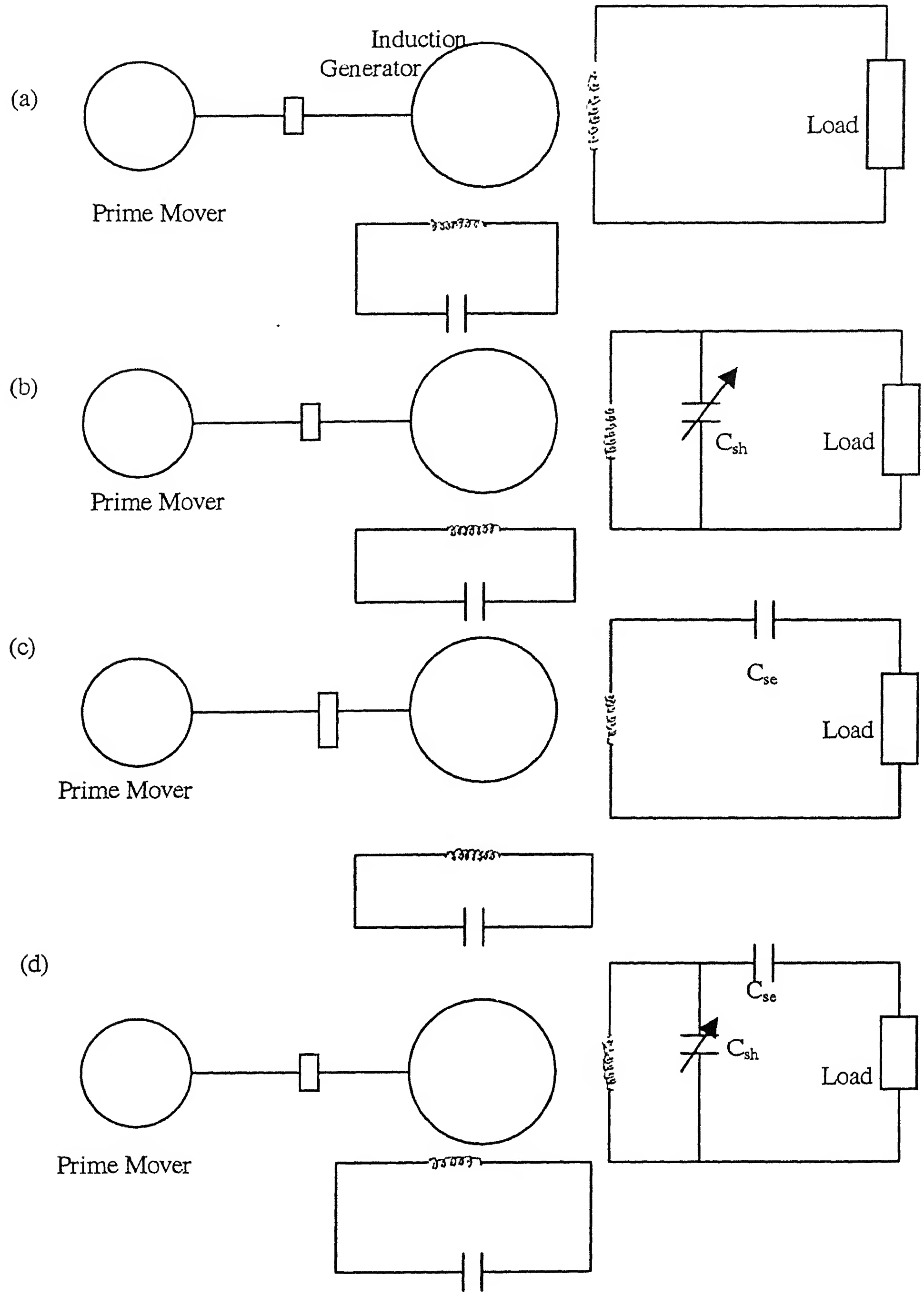


Figure 2.1 Schematic diagram of schemes if capacitor excitation of two-winding Single-phase Self-excited Induction Generator (a) General (b) Variable shunt (c) fixed series (d) Fixed series and variable shunt

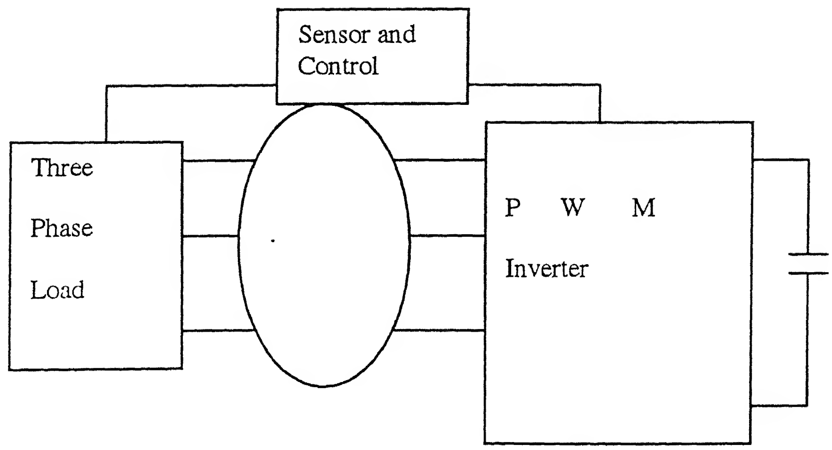


Fig.2.2.Physical diagram of the system proposed

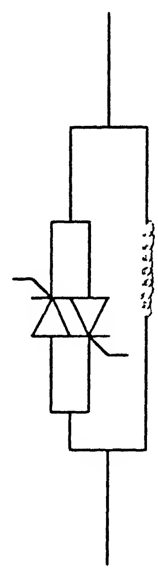


Fig.2.3 Thyristor controlled Rectifier

2.3 Analysis technique

The advantages of induction generator for renewable energy application has led to increased research on the analysis of SEIG. However, the potential of induction generator was realized in early eighties, when mathematical tools of the steady state analysis of the SEIG were made available [20-23]. The analysis of the SEIG is more complicated than the grid connected generators due to magnetic non-linearity. The methods for identifying the quiescent operating point under saturation for a given speed, load and capacitor can be divided in two categories as (a) Loop impedance technique and (b) nodal admittance technique. In loop impedance technique, two higher degree non-linear simultaneous equations as the function of per unit frequency and magnetizing reactance are obtained. They are derived by making the real and imaginary components of the complex loop impedance zero. These equations are solved by numerical methods like Newton-Raphson method etc. and with the help of the magnetization curve. The nodal admittance method considers the admittance connected across the nodes, which define the air-gap. A polynomial of per unit frequency is obtained by equating the sum of real parts to zero. After solving the polynomial, the per unit frequency is substituted in the equation, which

is obtained by making the imaginary parts of the nodal admittance zero. Then the magnetizing reactance is determined.

The analytical technique reported by Bhim et al[23] is based on loop impedance method where the two polynomials with the magnetizing reactance and per unit frequency as unknown variables are solved by Newton-Raphson method. They have described that the parameters responsible for self-excitation of an induction machine are shaft speed, residual magnetism, and the size of the capacitor connected to the machine. Quazene and McPherson [22] have reported an analysis based on nodal admittance technique. The equation is a fifth degree polynomial in per unit frequency and is solved by a numerical method.

The above reviewed literature mainly focused on the constant speed mode of operation assuming that the SEIG is operated with some form of turbine speed control. SEIGs driven by some wind turbines operate at variable speed. Sometimes, the SEIG in micro-hydro plants are driven by unregulated turbines due to cost considerations. Singh et al has [23] presented the effect of speed on the excitation requirement of the machine for no load and under loaded condition.

Relative to three-phase induction generators, only few publications have appeared dealing with the steady-state analysis and transient analysis of single-phase induction generators [24-33]. An experimental investigation on the single-phase SEIG for lighting loads has been reported by Singh et al [25] but no analysis was presented. The

results presented show that a voltage regulator is required for var compensation or maintaining the terminal voltage constant with the variation of load. But the cost and complexity of voltage regulator restricts the very advantages of recommending the squirrel cage induction machine for small portable units. The work reported by Murthy [26-27] deals the self-regulating features of single phase Self-Excited Induction Generator by connecting a capacitor in series with the load circuit. The mathematical model used for the analysis, however, is based on the simplification that the current in the magnetization reactance referred to the backward field is neglected. Since the forward rotating field is associated with a generator action and the backward rotating field is associated with plug-braking action, the predicted power output of the generator based on this assumption yield the optimistic result. Further, the paper is silent on the selection of value of series capacitor. Rahim et al [28]has shown that voltage regulation is better when the machine is excited through the auxiliary winding. The analysis reported by Chan [29] is concerned with the single-phase SEIG in which the excitation capacitance and electrical load are connected across terminals of the same winding and the per-unit frequency is determined independent of the magnetizing reactance with assumption that the magnetizing reactance referred to backward field is neglected. Both the research papers mentioned above neglect the core loss and the effect of series capacitor on the load characteristics. The analysis of Single-phase SEIG reported by Ojo [30-33], though useful, is not found to be comprehensive enough. For example, it does not cover the analysis of reactive current requirement to maintain terminal voltage constant. Jain et al [35] has proposed an efficient

iterative technique for the solution of the generated frequency of a three-phase self-excited induction generator. A simple algebraic equation is solved for initial value calculations and then Secant method is used for the solution of non-linear equation for the generated frequency. The proposed technique is simple in nature and is suitable for any kind of balanced load. Further, the core loss is also taken into consideration so as to get accurate results. The effectiveness of the technique is proved by comparing the theoretical results with the well-established Newton-Raphson technique with experimental results.

2.4 Conclusion

After the study of published literature as discussed in the preceding sections, it is realized that there is a need of further investigation towards the improvement in the SEIG system for simple and economically viable stand-alone power generation and to suggest an improved technique of analysis of such system. Relative to the study of steady-state properties, only few publications have appeared providing a control scheme for SEIG reactive power compensation with power-electronic interface.

CHAPTER 3
STEADY-STATE ANASLYSIS OF THREE-PHASE SELF EXCITED INDUCTION GENERATOR

3.1 INTRODUCTION

Self-excited induction generators are becoming more and more popular for supplying electrical energy in remote and rural areas due to its various advantages over the synchronous generator. The self-excited squirrel cage induction generators are cheap, robust, do not have separate DC excitation system and can be operated trouble free for many years. Therefore, self-excited induction generators are also well suited for generating electricity from non-conventional energy sources like biogas, wind, hydro heads etc., in isolated and remote locations.

Several attempts are made to analyze the performance of the self-excited squirrel cage induction generators. It is now well known that for the operation of induction generators in stand-alone mode, the capacitive excitation is necessary to maintain voltage across the machine terminals. If the speed of the machine is kept constant, the terminal voltage of the generator depends on the value of capacitance and load connected across its terminal. The voltage of the load decreases with increase in load for a fixed value of capacitance. Therefore, for regulating the terminal voltage, the capacitance across the machine terminal has to vary continuously with load. But the variation of capacitance is not an economical and simple proposition. However, if a small variation of terminal voltage, is permitted, the stepped switching of capacitors with the provision of making them on and off at variable

loads in place continuous variation of capacitance, may be economical and simple to use. Moreover, for the design of voltage regulator, the knowledge of capacitive VARS required at different speeds and loads is also of interest for a particular machine.

In this investigation, an attempt has been made for the determination of capacitive vars required by an Induction generator. Different performances are also analyzed in this chapter.

3.2 ANALYSIS

In the present study, the steady state equivalent circuit of induction machine is used (Fig3.1). The equivalent circuit is normalized to base frequency. In this equivalent circuit, R_s, R_r are per phase stator and rotor resistance referred to stator. X_{ls} and X_{lr} are per phase leakage reactance of stator and rotor referred to stator, respectively. The X_m is the magnetizing reactance per phase and X_c is the per phase capacitive reactance of the capacitance C connected across the machine terminals at base frequency. F and v are per unit frequency and speed. I_s, I_r, I_L are per phase stator, rotor (referred to stator) and load current, respectively. In case of cage machine, the stator and rotor leakage reactance are assumed to be equal in magnitude.

For the purpose of obtaining required lagging reactive power to maintain desired voltage at machine terminal, X_c and F are only unknown parameters for a given speed and load on the generator.

From fig3.1 the loop equation of the stator current can be written as

$$Z_s I_s = 0 \qquad \text{.....(3.1)}$$

Where,

$$Z_s = Z1 + ZcR_L / (Z_c + R_L) + Z_2 Z_m / (Z_2 + Z_m) \qquad \text{.......... (3.2)}$$

and,

$$Z1 = R_s + jFXls$$

$$Z_c = -jX_c / F$$

$$Z2 = R_2 F / (F - v) + jFXlr$$

$$ZM = jFX_m$$

Under steady state self-excitation, I_s can not be zero, therefore from equation (1) Z_s=0, which implies that the real and imaginary components of Z_s would be separately zero.

These equations can be expressed as

$$f(Xc,F) = F^3 A1 + F^2 A2 + F(A3Xc + A4) + A5Xc = 0 \ldots\ldots\ldots\ldots (3.3)$$

$$g(Xc,F) = F^2(B1Xc + B2) + F(B3Xc + B4) + B5Xc \ldots\ldots\ldots\ldots (3.4)$$

The above two non-linear equations have X_c and F unknown terms. These equations are useful for constant voltage analysis.

The constants are defined as (assuming xls = xlr = xl)

$$A1 = -(2Xm + Xl)R_L Xl$$
$$A2 = -A1v$$
$$A3 = (R_L + Rs + Rr)(Xm + Xl)$$
$$A4 = RsR_L Rr$$
$$A5 = -(Rs + R_L)(Xm + Xl)v \ldots\ldots\ldots\ldots (3.5)$$
$$B1 = (2Xm + Xl)Xl$$
$$B2 = R_L(Rs + Rr)(Xm + Xl)$$
$$B3 - -B1v$$
$$B4 = -RsR_L v(Xm + Xl)$$
$$B5 = Rr(R_L + Rs) \ldots\ldots\ldots\ldots (3.6)$$

In equations (3.5) and (3.6) all constants contain machine parameters, load resistance and speed. Out of these parameters only magnetizing reactance depends upon the magnetization characteristic of the machine. The magnetization characteristic of the machine can be expressed by the following mathematical relation :

$$X_m = (k_1 - Vg / F) / K_2$$

Where K_1 and K_2 are constants and depend upon the design of the machine.

The relationship between the air-gap voltage and terminal voltage is as follows:

$$V_g = VT /(1 - Z1/ZL_{sc}) \qquad (3.7)$$

$$ZL_{sc} = Z1 + ZL_c$$

$$ZL_c = ZcR_L/(Zc + R_L) \qquad (3.8)$$

The non-linear equations((3.3) and(3.4)) can be solved by NEWTON-RAPHSON method. In the NEWTON-RAPHSON method, the JACOBIAN matrix is computed as follows.

$$[J] = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \qquad (3.9)$$

Where,

$$J11 = \Delta f / \Delta Xc$$
$$J12 = \Delta f / \Delta F$$
$$J21 = \Delta g / \Delta Xc$$
$$J22 = \Delta g / \Delta F \qquad (3.10)$$

The initial value of $X_{co} = X_{mr}$ and $F = v$ at rated condition are considered. The increments h and k in values of Xc and F are given below:

$$\begin{bmatrix} h \\ k \end{bmatrix} = [J]^{-1} \begin{bmatrix} -fo \\ -go \end{bmatrix}$$

Where f_o and g_o are the values of equations (3.3) and (3.4) for initial values of X_C and F. The iteration process will continue until desired accuracy is obtained so that

$$|f(X_C, F)| < \varepsilon$$
$$|g(X_C, F)| < \varepsilon$$

Where epsilon is a small quantity say 10E-05.

After obtaining X_c and F, the following relations can be used to compute the machine performance (assuming VAR = Reactive power).

$$Is = V_g / \{ F (Z1 + ZLC) \} \qquad (3.12)$$
$$Il = Is . Zc / (R_L + Zc) \qquad (3.13)$$
$$VT = Il . R_L \qquad (3.14)$$
$$Ir = Is . ZM / (Z2 + ZM) \qquad (3.15)$$
$$VAR = 3 . VT^2 F / Xc \qquad (3.16)$$
$$Po = 3 . VT . Il \qquad (3.17)$$

However, to obtain the performance of the capacitor excited cage generator for the given values of capacitance and speed, the unknown parameters in the equivalent circuit of the machine, are only X_m and F. The equations used for the steady-state performance analysis are as follows

$$f(Xm, F) = F^2(C1Xm + C2) + F(C3Xm + C4) + C5 = 0.....(3.18)$$

$$g(X_m, F) = F^3(D1X_m + D2) + F^2(D3Xm + D4) + F(D5Xm + D6)$$
$$+ D7Xm + D8 = 0.......... ....(3.19)$$

Where (assuming xls =xlr =xl)

$$C1 = R_L(R_s + R_r) + 2XcXl$$
$$C2 = R_L(Rs + Rr) + XcXl^2$$
$$C3 = -RsR_Lv - 2XcXlv$$
$$C4 = -RsR_LvXl - Xcvxl^2$$
$$C5 = -XcRr(R_L + Rs)$$
$$D1 = X2XlR_L$$
$$D2 = -Xl^2R_L$$
$$D3 = -D1v$$
$$D4 = -D2v$$
$$D5 = (R_L + Rs + Rr)Xc$$
$$D6 = (R_L + Rs + Rr)XcXl + R_LRr(Xc + Rs)$$
$$D7 = -Xc(R_L + Rs)$$
$$D8 = D7Xl ....(3.20)$$

The equations are 2nd and 3rd order simultaneous algebraic equations and can be solved by NEWTON-RAPHSON method.

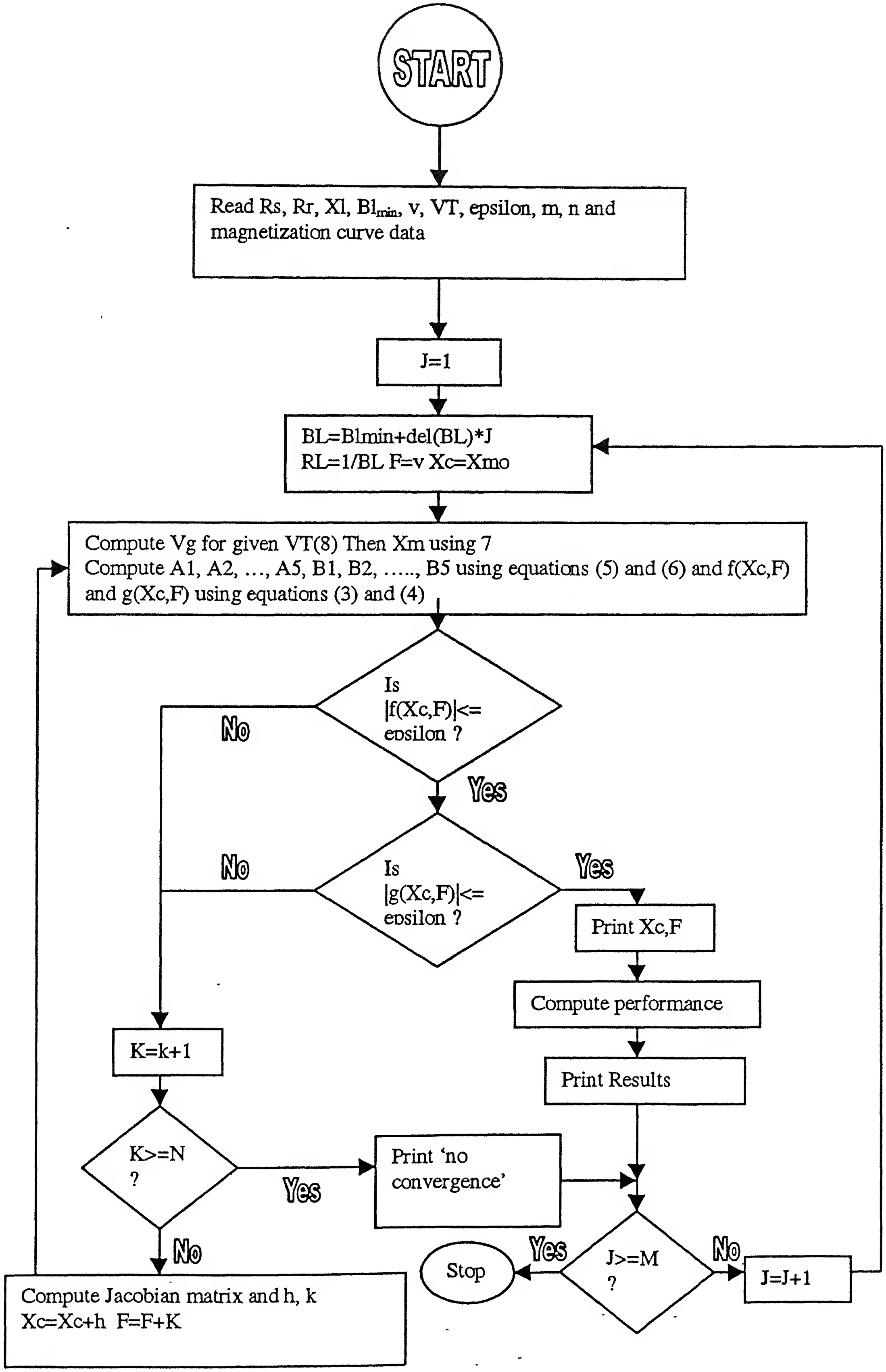


Fig6.0.1.Flow-chart diagram of steady-state analysis at constant output voltage

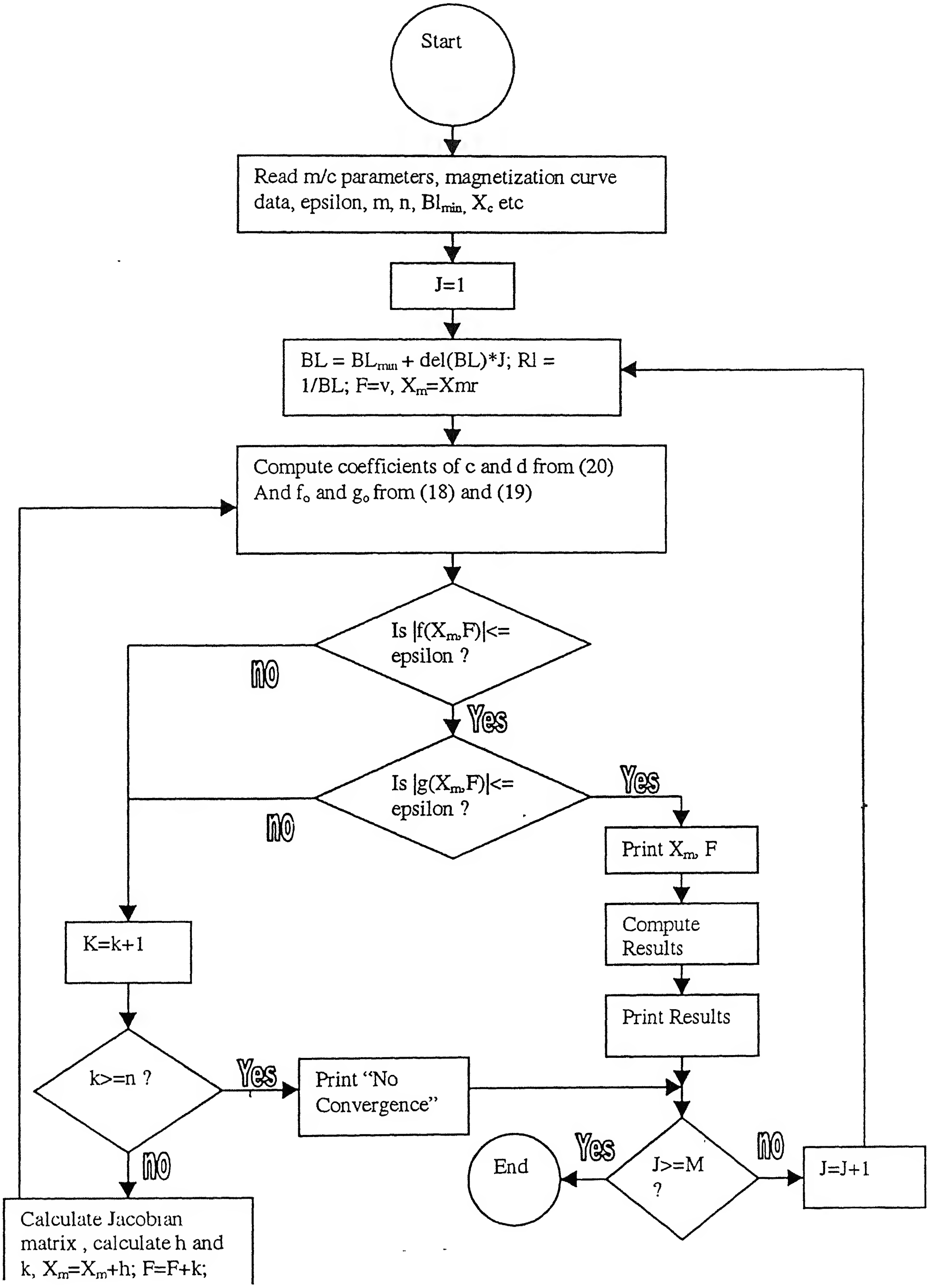


Fig.6.0.2. Flow-chart diagram of steady-state analysis at constant capacitor

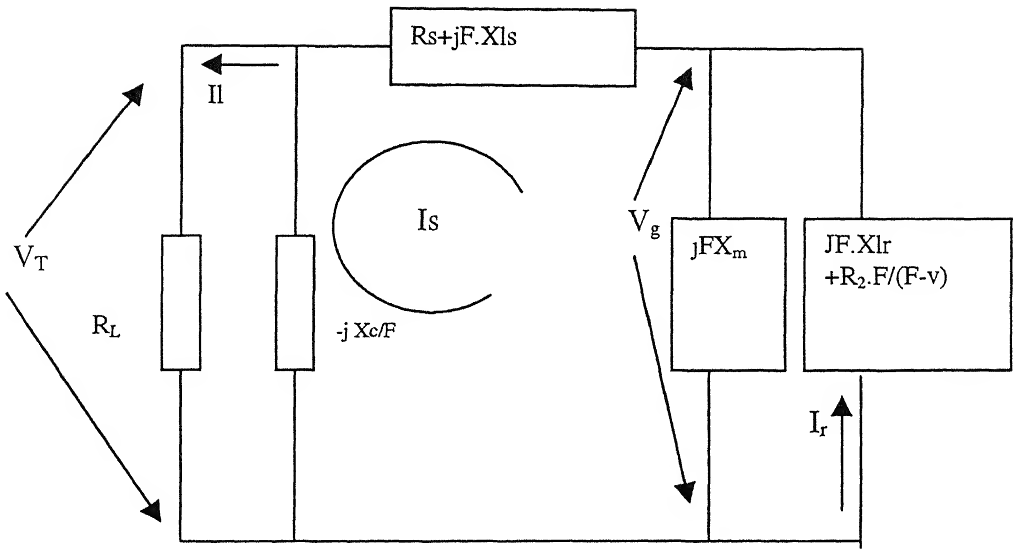


Fig. 3.1 Equivalent circuit of 3-phase SEIG

3.3RESULTS AND DISCUSSION

The performance characteristics of a capacitor excited, 3.7KW, cage generator are obtained (ratings given in appendix B). These are plotted in Fig 3.2 to 3.11.The following salient features are observed.

(1) The full load characteristic (Fig.3.2) of the machine shows that the terminal voltage of the machine increases with increase in capacitance and the rise of voltage is limited by the saturation of the magnetic circuit of the machine. Decrease in capacitance reduces the terminal voltage till capacitance is equal to the critical capacitance (below which the machine loses excitation).

(2) The variation of reactive power with output power for rated terminal voltage is computed (Fig.3.3). The load is varied between 2.5kw and 4kw at rated speed. For constant terminal voltage, the value of VAR increases with output power. In our proposed scheme a fixed valued capacitor is connected in shunt to the SEIG. It supplies a VAR, which is the average of the VAR requirements at 4kw and 2.5kw. The calculated value of capacitance is 53.4 microfarad. The rest of the reactive power is supplied or consumed by the SLCVC (Fig.3.4). The result shows the SLCVC operates at both inductive and capacitive modes. It also shows that, for an increase in output power of the machine at rated speed, the reactive power has to vary continuously for regulating the machine terminal voltage.

Fig3·2 Variation of V with C at rated load and speed

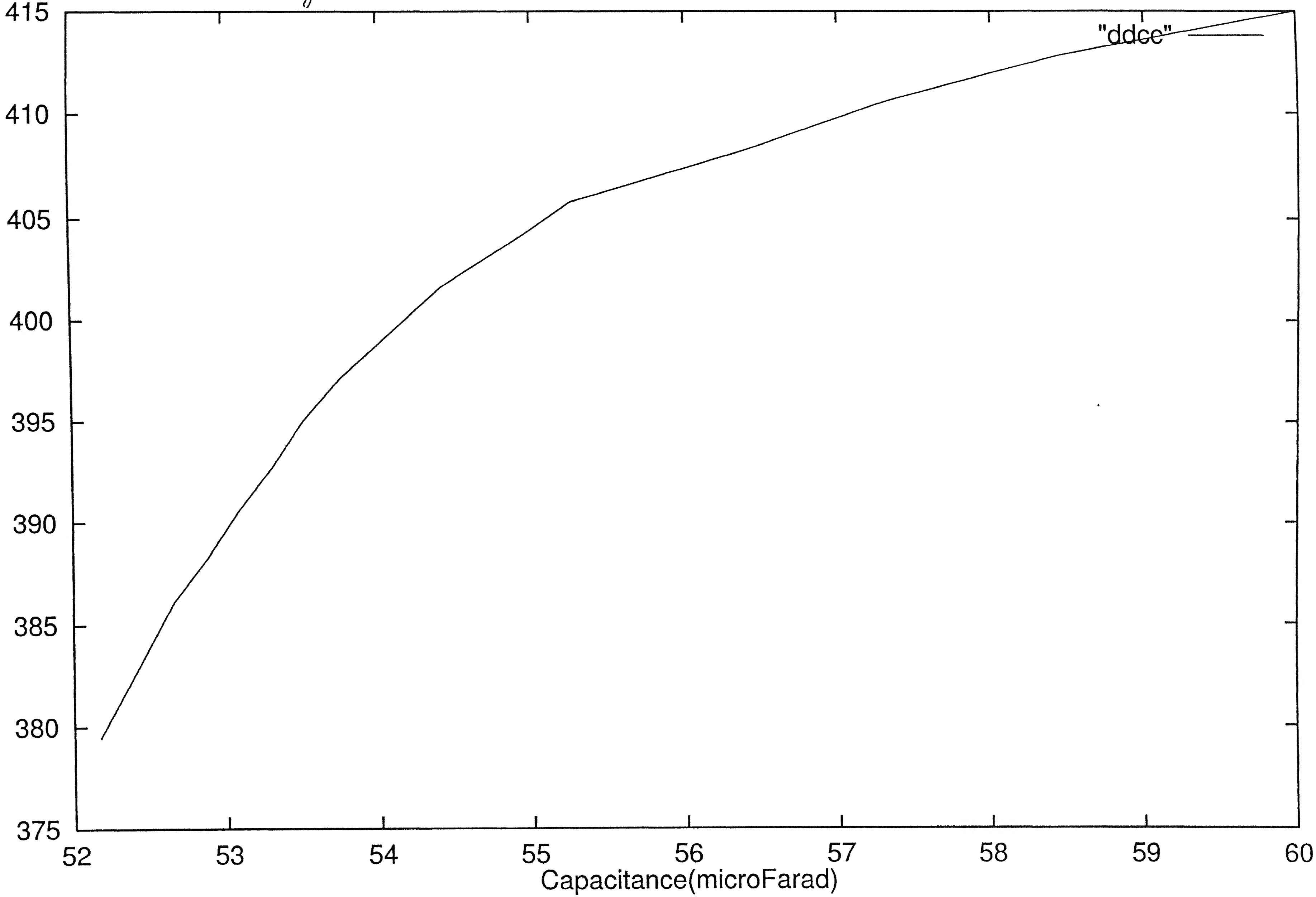


Fig 3·3 Compensating Var vs Load Power(Const Generated Voltage)

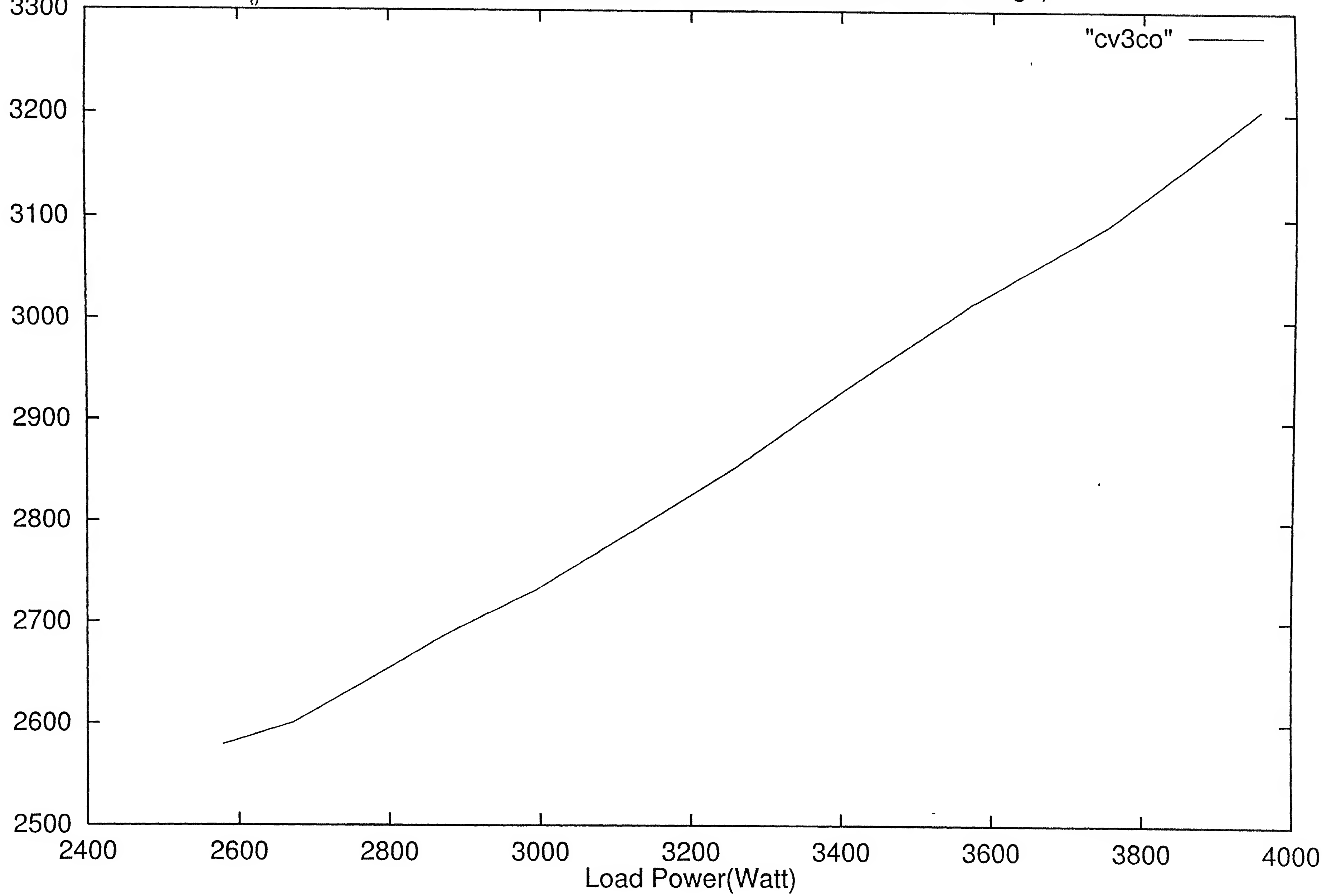


Fig 3·4 SLCVC Compensated VAR vs Load Power

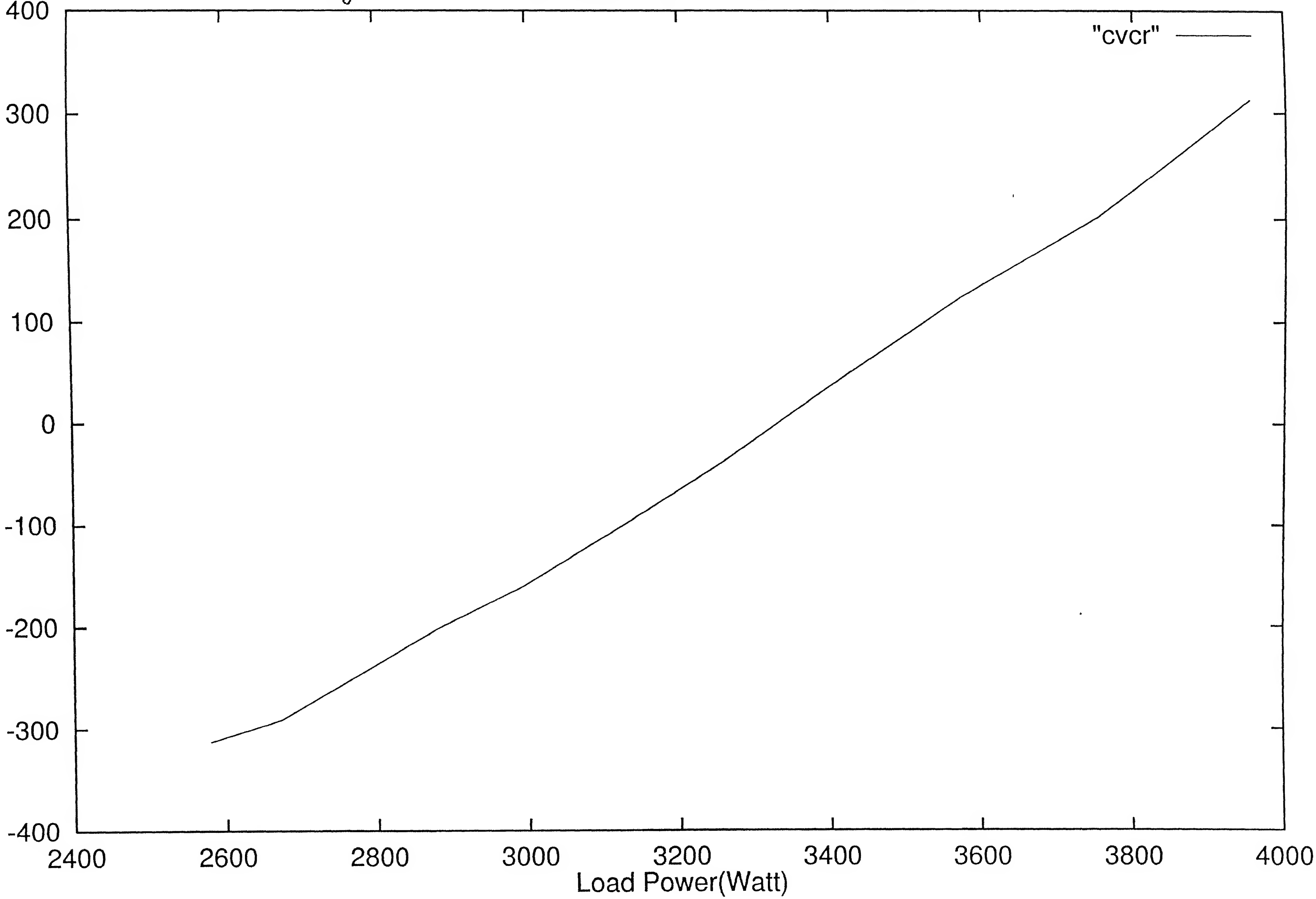


Fig 3.5 total C at variable speed(gen volt const)

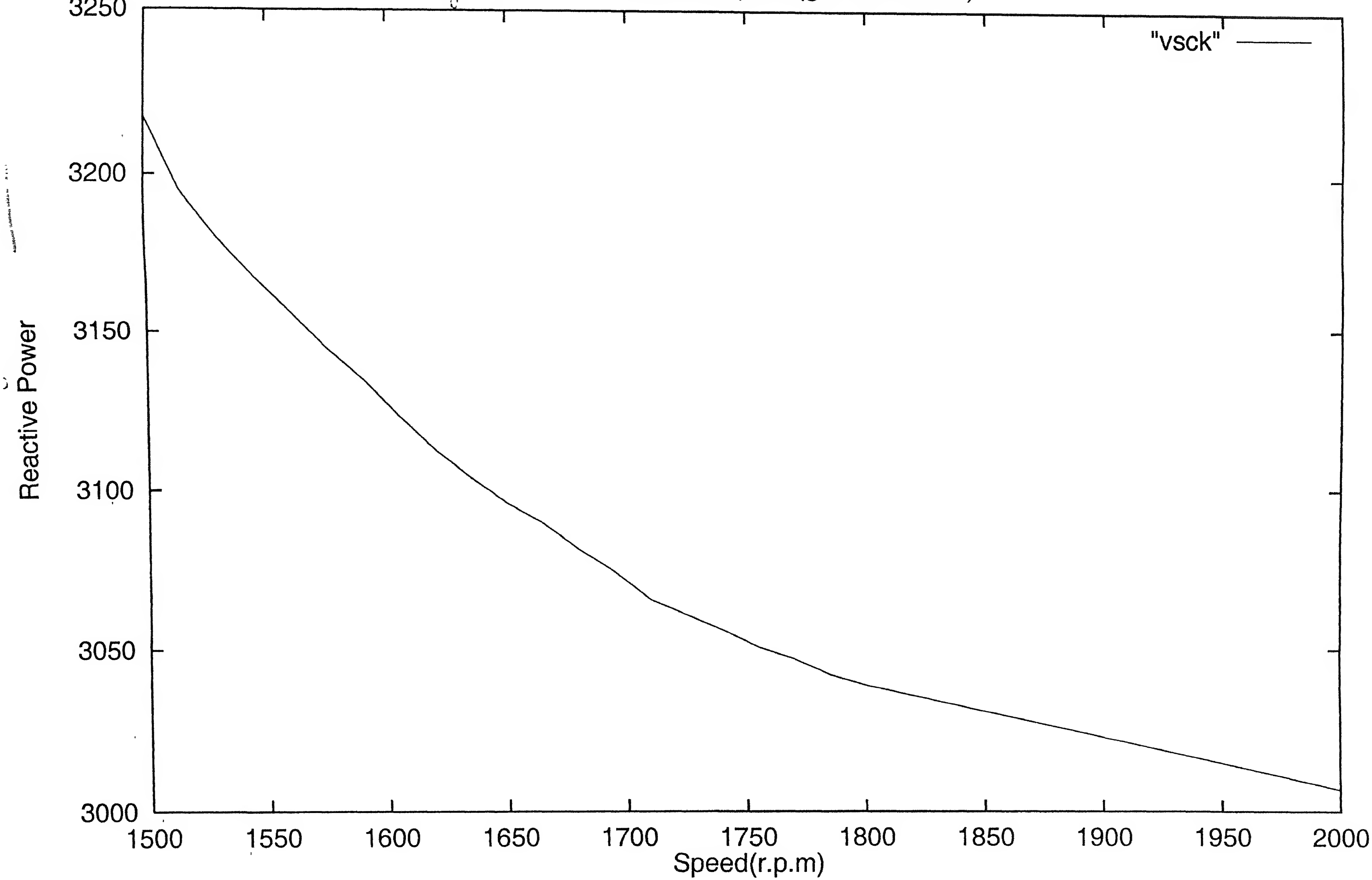
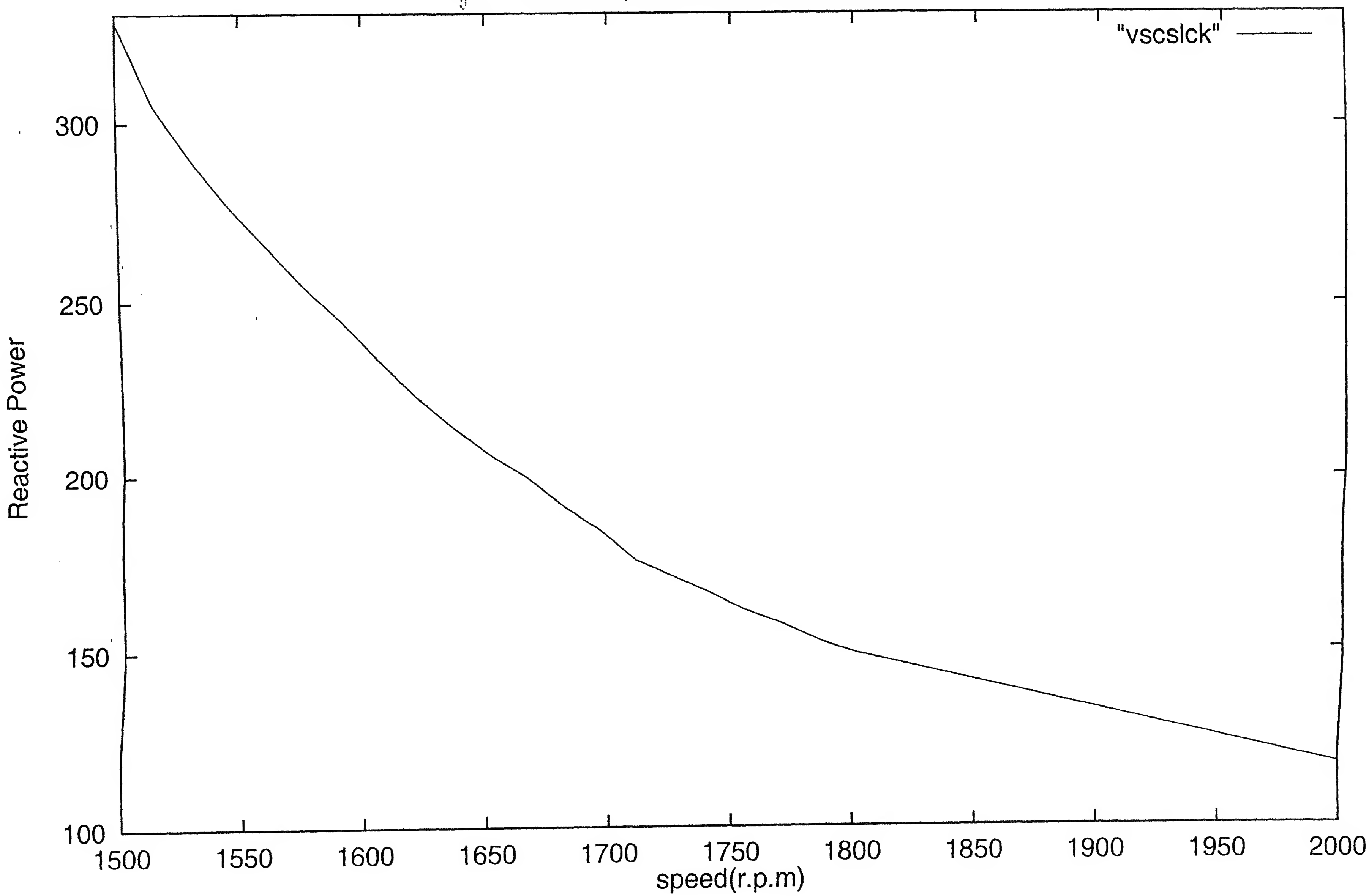
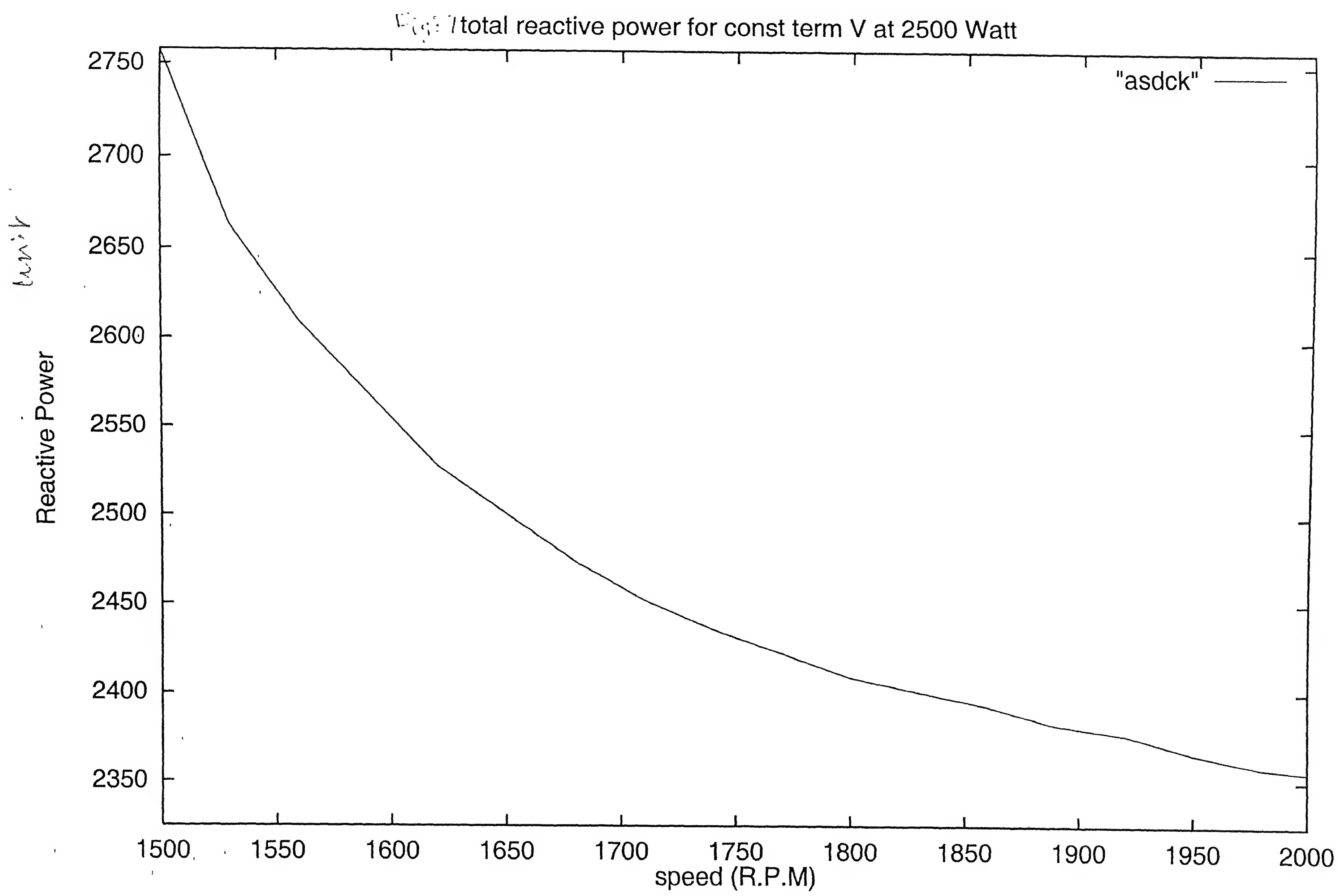
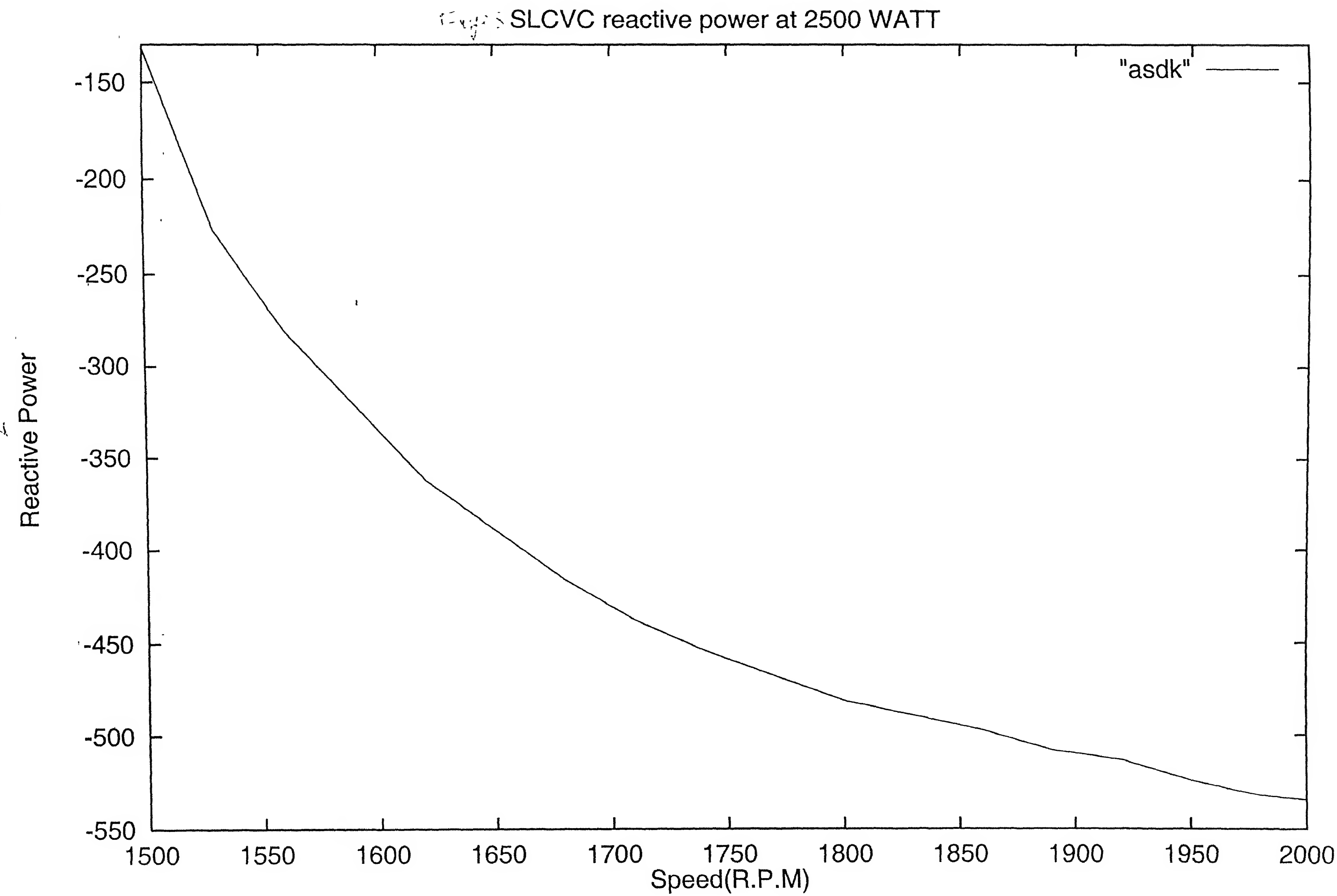


Fig 3·6 reactive power supplied by SLCVC





total reactive power for const term V at 2500 Watt
"asdck"
Reactive Power
speed (R.P.M)
2750
2700
2650
2600
2550
2500
2450
2400
2350
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000



SLCVC reactive power at 2500 WATT
"asdk"
Reactive Power
-150
-200
-250
-300
-350
-400
-450
-500
-550
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Speed(R.P.M)

Fig. 3.9 Generated Frequency vs Load Power(with SLCVC)

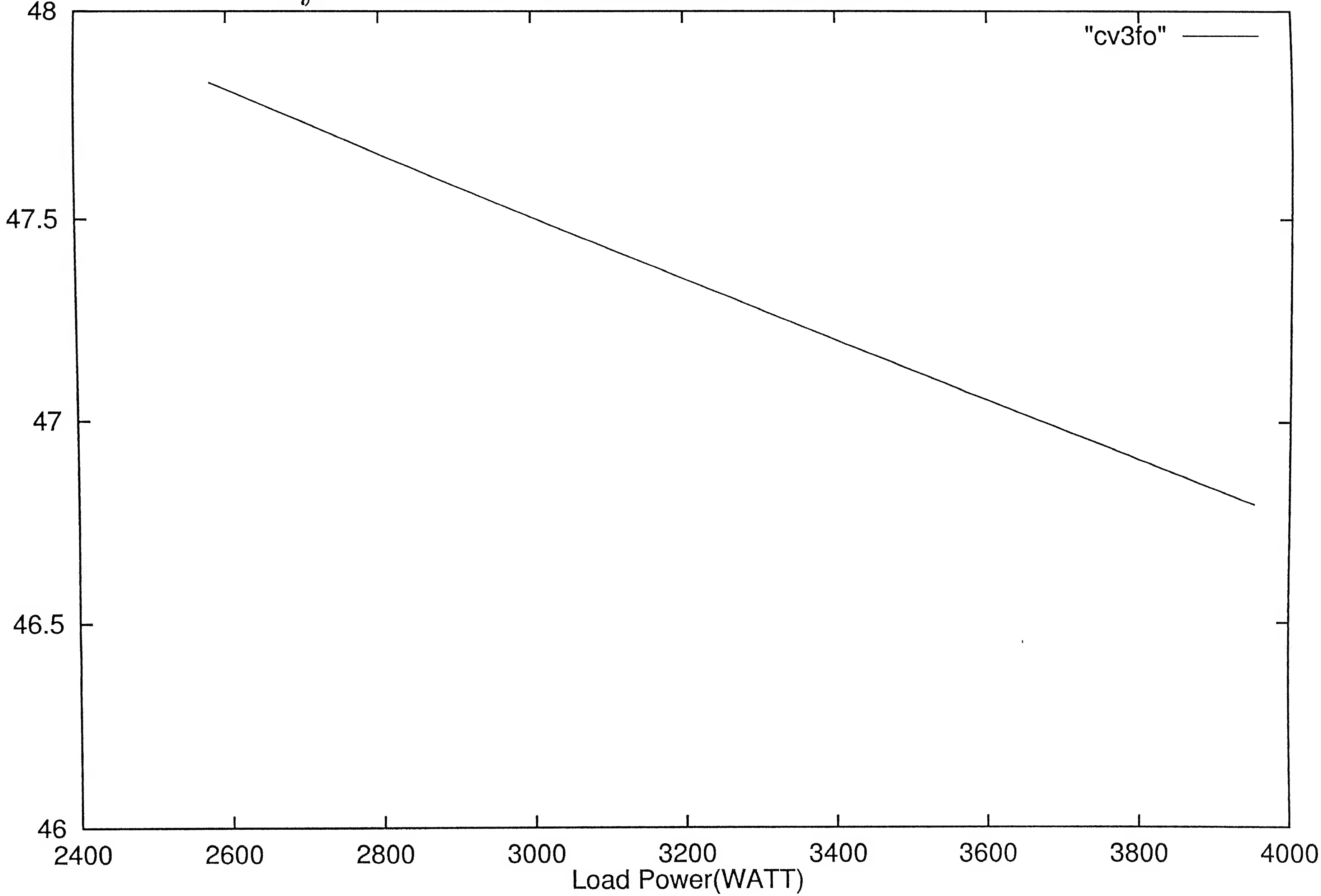


Fig 3 10 Generated frequency vs Load Power(without SLCVC)

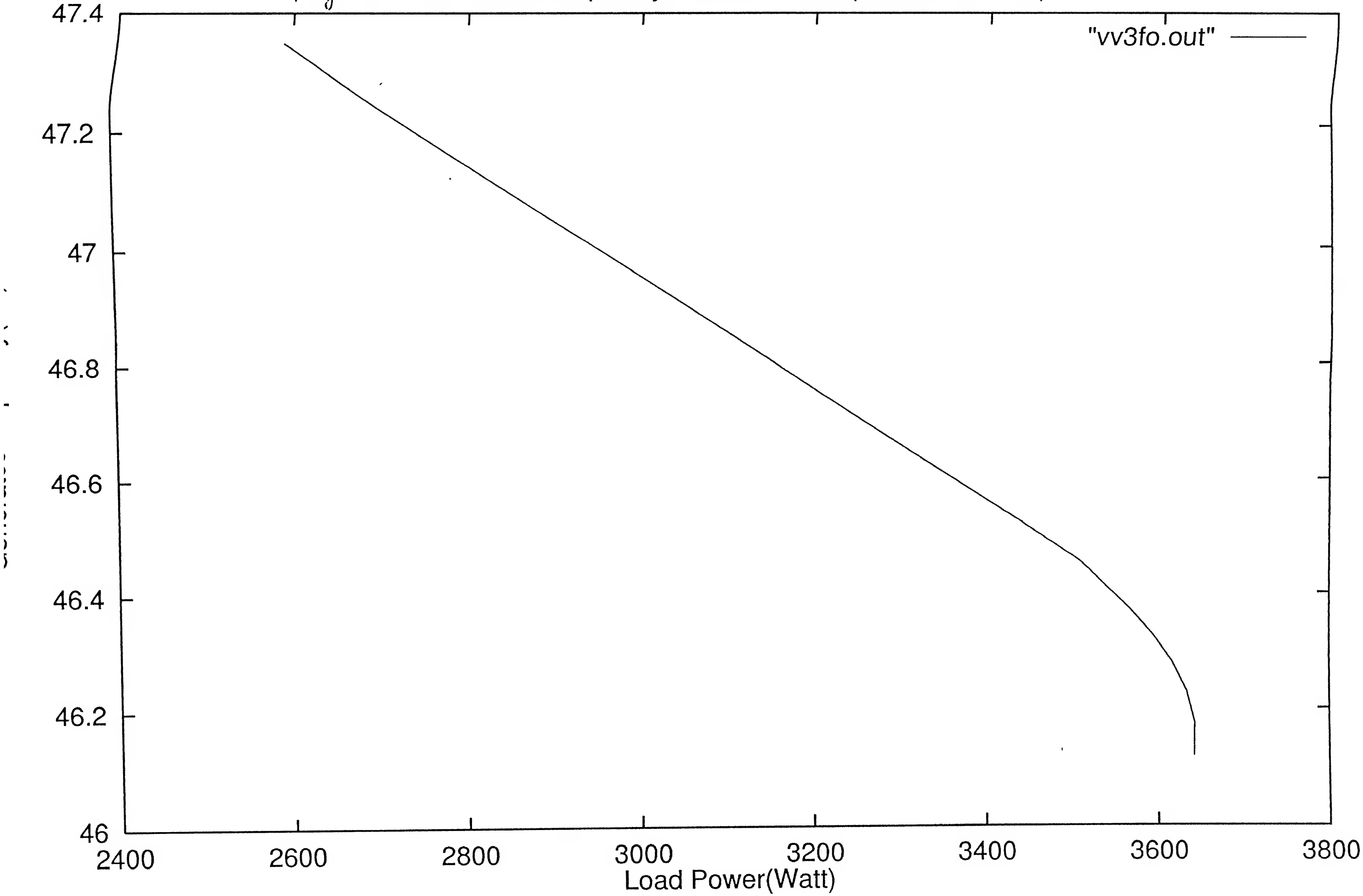
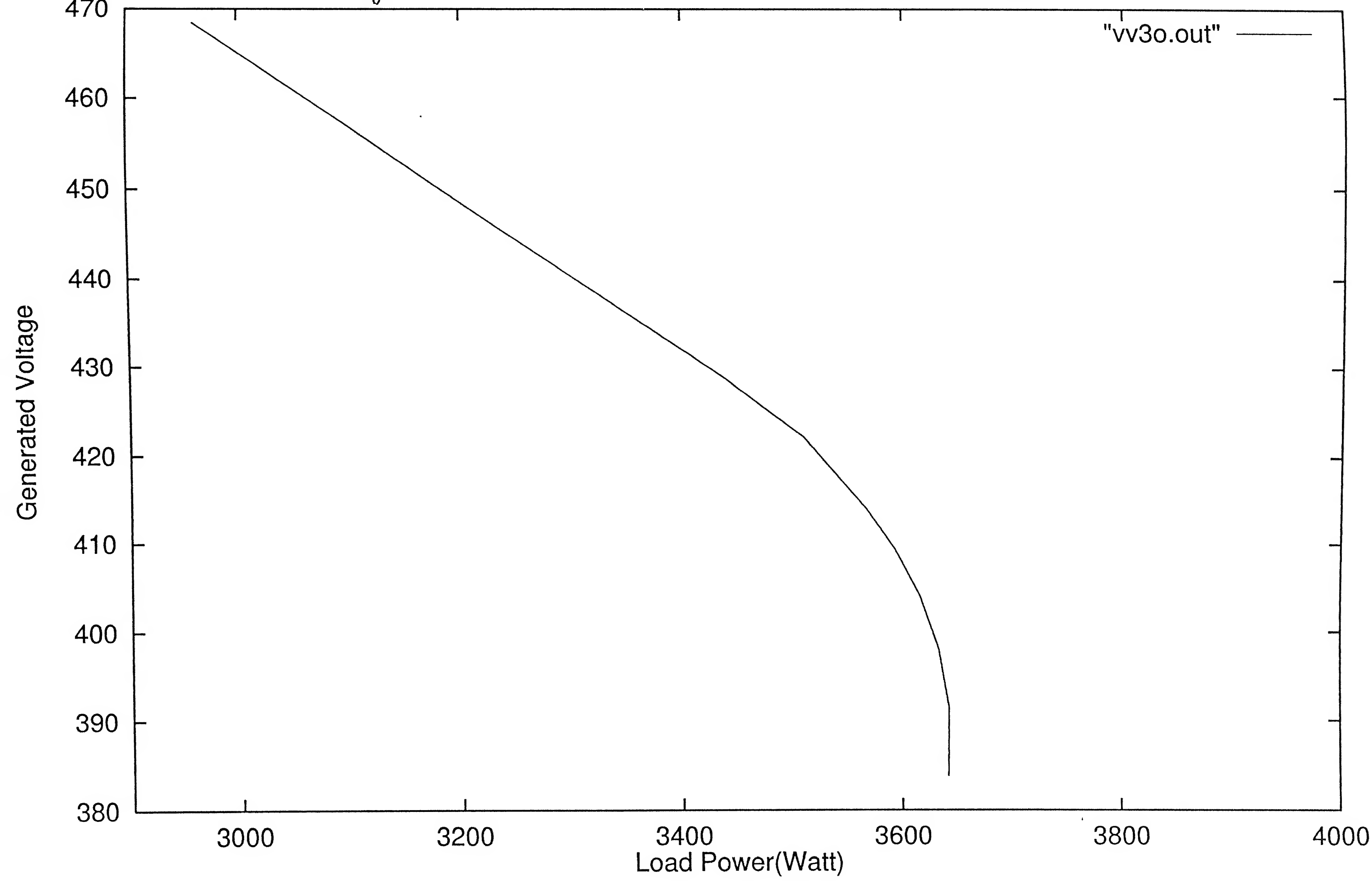


Fig 3-11 Generated Voltage vs Load Power(without SLCVC)



(3) For a variable speed prime-mover, the effect of speed on the excitation requirements by the machine is also studied (Fig3.5-3.8). The variation of speed with reactive power requirement to maintain the terminal voltage constant at rated value under loaded condition of the machine is studied. There is a fixed capacitance in parallel with SLCVC. The rest of the inductance or capacitance are supplied by the SLCVC. The SLCVC acts as a variable capacitor or inductor. The computations are made both at 4kw and 2.5kw. It may be noted that the reactive power requirement reduces with the increase of speed. It may also be observed that the machine requires higher value of reactive power at full load compared to reduced load condition of the generator. It is seen from the frequency-power characteristics that the frequency is now nearer to 50 Hz (Fig.3.9) than the case, in which SLCVC was not there in the circuit.

(4) The load characteristic of the machine in terms of terminal voltage and frequency with variation in output power for a value of capacitance of 53.4 microfarad at the rated value of speed, is also studied (Fig.3.10-3.11). The fall in voltage with increase in load, is observed due to effect of armature reaction, impedance drop and its dependent excitation. The characteristic shows that the machine behaves like a dc self excited generator with a field resistance. The increase of capacitance (over-excitation) also increases the output power, which should be stopped if the current exceeds its rated value.

3.4Conclusion

The performance characteristics of the machine are obtained by an analytical technique. From the obtained characteristics of the machine, it is concluded that the continuous variation of excitation with load is necessary for regulating the voltage of the machine and the reactive power requirement of the machine reduces with the increase in speed. Therefore, an SLCVC-capacitor combination for regulating the terminal voltage of the machine at rated value will be useful and may force the machine to run at its maximum capacity.

CHAPTER 4

ANALYSIS OF SLCVC BASED SOLID-STATE VOLTAGE REGULATOR FOR SEIG

4.1.Introduction

The increased emphasis on renewable energy sources has accelerated research and development of the SEIG for autonomous power generation. It has been emerged as a very good candidate of autonomous power generation due to simplicity, ruggedness and low cost. The fundamental problem in using the SEIG is its inability to control the terminal voltage and frequency under variable load condition. It needs an external source of reactive current for self – excitation and subsequently sustaining it with load variation. Limitation of autonomous induction generator with capacitor excitation are poor voltage and frequency regulation, limited output power and load voltage collapse when the generator is loaded beyond attainable maximum steady-state power output. The poor voltage regulation of the machine results in under-utilization of machine. In order to utilize the machine to its rated capacity it becomes essential to regulate the terminal voltage with load. In practice to counter these limitations variable capacitor, thyristor controlled static var compensator, saturable core reactor, pulse-width modulated converters are used.

While the use of switched capacitor is cheaper, it regulates the terminal voltage in steps. Static Var Compensator(SVC) uses either thyristor-switched capacitor(TSCs) or a thyristor controlled

reactor(TCR) with fixed capacitor. Functionally, the thyristor-controlled static var compensators is a controllable reactive impedance. The controlled switching of thyristor changes the current drawn by the capacitor or reactor. Therefore, the reactive power generated or consumed by them also changes. Consequently, the capacitor bank or the inductor bank are rated for the full reactive current. For this reason, SVCs are large systems involving a number of important components. Moreover, the inductor switching also injects harmonics in the line current of the system.

Static Condenser(SLCVC or STATCON)

The application of modern semiconductor devices, power converter circuit and control circuits have resulted in a number of solid-state var sources. Solid-state synchronous voltage sources (SVS) employ a dc to ac inverter, which internally generates capacitive/inductive reactive power without the use of ac capacitors/reactors. These type of compensators are proposed in all kind of power systems. It can be used for shunt compensation, series compensation and phase angle control.

Availability of reliable, fast and solid-state switches such as MOSFETS and IGBTs and decrease in their cost, have led to investigate the use of solid-state VAR sources in SEIG system so that it can be made a viable option of power generation while competing with conventional synchronous generator.

The SVS operated as a reactive shunt compensator, exhibits V-I characteristics similar to the rotating synchronous compensator. Therefore, this specific arrangement of SVC is called STATCON. The STATCON is a voltage-source inverter that produces a set of three-phase output voltages. These output voltages are in phase with ac system voltage and are coupled to it by a relatively small inductive reactance. The output voltage of the STATCON (SLCVC) is generated by a dc to ac inverter with a dc capacitor. The instantaneous power at the ac terminals of the SLCVC must always be equal to the instantaneous power at the dc terminals when there is no power loss in the converter. Since reactive power at zero frequency is zero by definition, the dc capacitor supplies no reactive power to the system. With the proper switching signals applied to the switching devices, it simply interconnects the three output voltages in such away that the reactive output currents can flow between the phases. Viewing this from the terminal of ac system, one could say that the inverter establishes a circulation of reactive power exchange among the phases. STATCON has no inertia and has much faster response. It requires less maintenance than its rotating counterparts. The SLCVC can be operated over its full output current range even at very low system voltage levels.

This chapter explores the use of SLCVC for close loop control of terminal voltage of an SEIG at varying load conditions. To start with, theoretical generation of controllable var using a voltage source inverter is briefly reviewed. The principle of operation of SLCVC and control approach for regulating the terminal voltage of SEIG is described. The

d-q axes model in stationary reference frame, which is widely used for the analysis of induction machine is used for simulating the effectiveness of the SLCVC based voltage regulator for controlled supply of excitation current required for controlling the terminal voltage of SEIG in synchronism with load.

4.2 System Description, Principle of operation and control scheme

The proposed scheme of regulating the terminal voltage of SEIG involves a 3.7kw, 415V star connected cage induction machine(ratings given in appendix B). The description of the scheme, principle of operation and the control scheme employed are given in a sequence as follows.

4.2.1 System Description

The main part of the system configuration consists of a three-phase IGBT based Current Controlled Voltage Source Inverter and an electrolytic capacitor at its DC link. The ac output terminals of the voltage source converter is connected to the ac mains of the SEIG through a filter reactance. The SLCVC has no energy storage element except an electrolytic capacitor on the dc link. Small real power is required to compensate the internal losses of the inverter and keeping the dc bus capacitor charged at a specific voltage level. The prime-

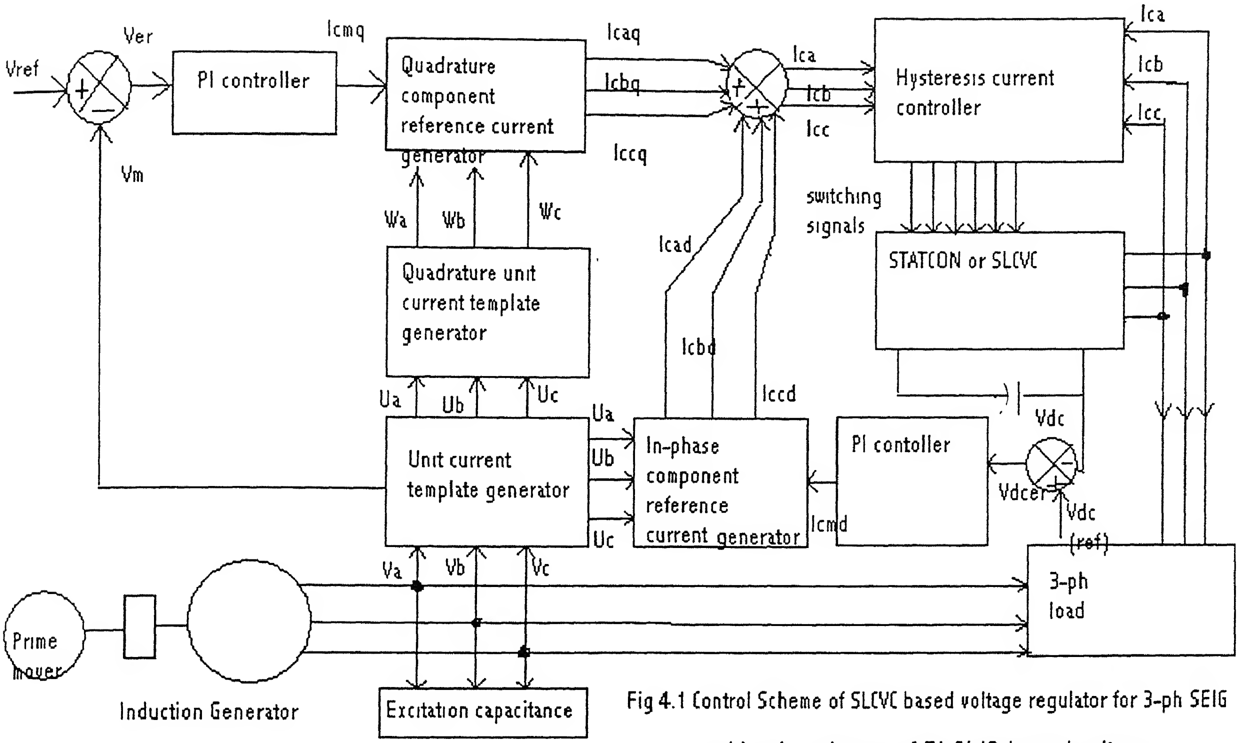
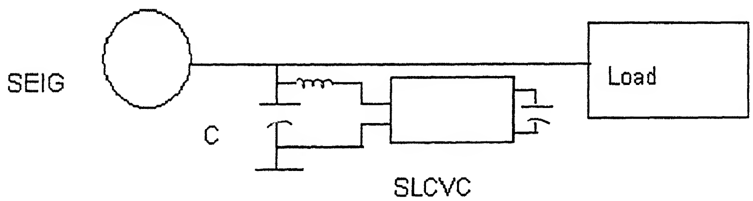


Fig 4.1 Control Scheme of SLCVC based voltage regulator for 3-ph SEIG

and basic scheme of SLCVC based voltage regulator



mover may be micro-hydro or oil driven engine. The fixed value excitation capacitor C supplies the exciting current required to maintain the terminal voltage constant at a particular operating point. It is also used for starting. The SLCVC, which is connected parallel to the excitation capacitor, acts as a source of leading or lagging current. Thus reactive power to be supplied by the SLCVC reduces.

4.2.2 Principle of operation

The quadrature components of SLCVC reference currents are computed so that the SLCVC supplies a leading current when the ac system voltage is less than the reference voltage (positive voltage error). The switching function derived from the hysteresis current controller increases the amplitude of the output voltage of the SEIG system. Then the current flows from the SLCVC to the SEIG system through the filter reactance and the SLCVC supplies a reactive (capacitive) power to the ac system. In the case when ac voltage of the SEIG system is greater than the reference voltage, the reference currents are so computed so that the SLCVC currents lag the corresponding voltages by an angle of 90 degrees. The switching function in the hysteresis current controller reduces the output voltage of the SEIG system. The SLCVC consumes reactive power and the current flows from the ac system to the SLCVC. When the voltage error is zero, the reactive current exchange will remain at constant level. The reactive power exchange between the SLCVC and ac system is directly

proportional to the q-axis component of the SLCVC current, which in turn depends upon the voltage error.

4.2.3 Control Scheme

The control scheme is used to regulate the terminal voltages of SEIG by controlling the reactive currents of SLCVC. For this, the ac voltages sensed at the SEIG terminal are compared with the reference voltage. The voltage error is processed in PI controller. The output of the PI controller controls the amplitude of the reactive current supplied or absorbed by the SLCVC.

The unit vectors u_a, u_b, u_c are three phase sinusoidal functions computed by dividing the terminal voltages by their peak values. Another set of unit vectors of w are sinusoidal function having phase shift of 90 degrees (leading) with the corresponding unit vectors of u. Multiplication of w vectors by the output of the PI controller yields the q-axis component of the SLCVC reference currents. These are the ideal currents, which must be supplied by the SLCVC in order to regulate the voltage of SEIG at a set reference value. They lead 90 degrees with their corresponding terminal voltages for positive sign of the controller output. Alternatively, they lag by 90 degrees with the corresponding voltages for the negative sign of the controller output. In other words, the SLCVC operates in capacitive and inductive modes respectively for positive or negative sign of the controller output.

It is well known that the semiconductor switches of the inverter have losses. If these losses are not supplied by the ac source, the energy stored in the dc capacitor is used. This results in discharge of the dc voltage of the capacitor. To meet the losses of the VSI and capacitor, a small phase difference is allowed between the SEIG output voltage and the output voltage of the voltage source inverter (i.e. the angle delta). For this purpose, the d-axis component of the SLCVC reference current is computed to charge the capacitor. The output of another PI controller is multiplied to u vectors to get the d-axis component of SLCVC reference current. This is done to maintain the dc capacitor voltage constant. The sum of quadrature and in-phase components of the above reference currents give the reference SLCVC three-phase currents.

Hysteresis current control is a method of controlling a voltage source inverter so that an output current is generated which follows reference current wave-form. This method controls the switches in the inverter asynchronously to ramp the current through the inductor up and down so that it follows the reference current. The hysteresis controller controls the SLCVC current in the band around the desired reference current. For the same, the sensed current signal at the output of SLCVC is compared with the reference current signal and the resulting error signal becomes the input of the hysteresis controller. When the current through the inductor exceeds the upper hysteresis limit, a negative voltage is applied by the inverter to the inductor. This causes the current in the inverter to decrease. Once the current reaches the lower hysteresis limit, a positive voltage is applied by the inverter.

As a result the current increases and the cycle repeats. The switching frequency is controlled by altering the width of hysteresis band, the size of the inductor, the dc voltage applied by the inverter to the inductor. The fast ON/OFF switching operation of IGBTs forces the SLCVC currents to follow the reference SLCVC currents.

SYSTEM MODELING

The mathematical model of the control scheme consists of many segments. They are given in sequence as follows.

1 Modeling of SEIG

The voltage and current relationship of the SEIG is expressed as

$$[v] = [R][i] + [L]p[i] + [G][i]w \qquad \text{...(4.1)}$$

It can be written in current-state-space derivative form as

$$p[i] = [L]^{-1}\{[v] - [R][i] - w[G][i]\} \qquad \text{...(4.2)}$$

Where, p(=d/dt) is a time derivative, [v],[I].[R],[L]and [G] are voltage, current, resistance, transformer inductance and rotational inductance matrices (Appendix A).

The developed electromagnetic torque and the torque balance equations are as:

$$T_e = (\frac{3}{2})(\frac{P}{2})L_m(i_{rd}i_{sq} - i_{rq}i_{sd}) \text{..(4.3)}$$

The torque balance equation may be expressed in speed derivative form as

$$p[w]=(\frac{P}{2J})(T_e - T_{shaft}) \qquad (4.4)$$

Initiation of self-excitation is based on residual magnetism in the rotor circuit and voltage builds up with the support of reactive current supplied by the fixed capacitor. The SLCVC is switched-on after the voltage builds up to stable value. The SLCVC capacitor should be charged before starting the switching operation. The equations governing the voltage across the capacitor as:

$$p[q_c]=[i_s]-[i_L]-[i_c] \qquad (4.5)$$

$$[v_s]=\frac{1}{C}[q_c] \qquad (4.6)$$

Where,

$$[i_s]=[i_{ds} \quad i_{qs}]^T$$

$$[i_L]=[i_{dL} \qquad i_{qL}]^T$$

$$[i_C]=[i_{dC} \qquad i_{qC}]^T$$

$$[v_s]=[v_{ds} \qquad v_{qs}]^T$$

$$[q_c]=[q_{cd} \qquad q_{cq}]^T \quad \text{..........} (4.7)$$

The SLCVC current matrix [i_c] can be obtained using the Park's transformation of the three-phase currents of the SLCVC.

2 Modeling of SLCVC

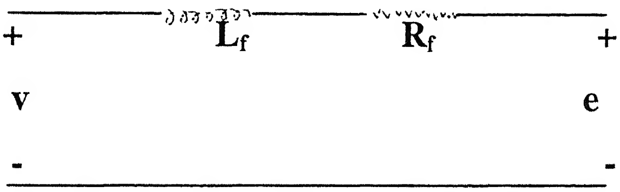
The SLCVC is operating in current controlled mode and modeled by the following state space equations:

$$pi_{ca}=-\frac{R_f}{L_f}i_{ca}+\frac{1}{L_f}(v_a-e_a) \quad \text{..........} (4.8)$$

$$pi_{cb}=-\frac{R_f}{L_f}i_{cb}+\frac{1}{L_f}(v_b-e_b) \quad \text{..........} (4.9)$$

$$pi_{cc} = -\frac{R_f}{L_f} i_{cc} + \frac{1}{L_f}(v_c - e_c) \qquad \text{.........(4.10)}$$

The above equations are derived considering the ac link of the SLCVC. L_f and R_f are the ac link inductance and resistance respectively. The resistive component R_f represents the power loss component of the entire converter.



Assuming SA, SB and SC are switching functions stating the on/off positions of Voltage Source Inverter-bridge switches, the equation for DC side voltage is

$$pv_{dc} = \frac{(i_{ca}SA + i_{cb}SB + i_{cc}SC)}{C_{dc}} \qquad \text{.........(4.11)}$$

V_a, V_b, V_c are three phase sinusoidal ac terminal voltages of SEIG.

The DC side voltage is reflected at the output of inverter in the form of three phase PWM ac voltages. These voltages may be expressed as:

$$e_a = V_{dc}\frac{(2SA - SB - SC)}{3} \qquad \text{.........(4.12)}$$

$$e_b = V_{dc}\frac{(-SA + 2SB - SC)}{3} \qquad \text{.........(4.13)}$$

$$e_c = V_{dc}\frac{(-SA - SB + 2SC)}{3} \qquad (4.14)$$

$$w_b = \frac{\sqrt{3}}{2}u_a + \frac{1}{2\sqrt{3}}(u_b - u_c)$$

$$w_c = \frac{\sqrt{3}}{2}u_a + \frac{1}{2\sqrt{3}}(u_b - u_c)$$

The reference currents of SLCVC consist of two components: in-phase component and quadrature component. They are estimated in sequence as follows.

The quadrature component of the SLCVC reference current is derived from the voltage error between the peak value of the ac voltage at the SEIG terminal and set reference voltage. The voltage error at the n-th sampling instant is

$$V_{er(n)} = V_{ref(n)} - V_{m(n)} \quad \text{...(4.16)}$$

The output of the PI controller at n-th sampling instant is expressed as

$$I^*_{cmq(n)} = I^*_{cmq(n-1)} + k_p\{V_{er(n)} - V_{er(n-1)}\} + k_i V_{er(n)} \quad \text{...(4.17)}$$

Where, Kp and Ki are respectively proportional and integral constants of the proportional Integral controller (PI) and superscript * represents the reference quantity.

The quadrature components of the SLCVC reference currents are estimated as:

$$i_{caq}^{*} = i_{cmq}^{*} w_a$$

$$i_{cbq}^{*} = i_{cmq}^{*} w_b$$

$$i_{ccq}^{*} = i_{cmq}^{*} w_c \text{.......................................} (4.18)$$

The in-phase component of SLCVC current is responsible for keeping the DC bus voltage at specified level. Hence, the in-phase component of the SLCVC current is derived from the voltage error between the DC bus voltage and the reference dc bus voltage.

The dc bus voltage error at the n-th sampling instant is

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \text{...............................} (4.19)$$

The output of the PI controller over dc bus voltage of SLCVC at the n-th sampling instant is expressed as

$$I_{cmd(n)}^{*} = I_{cmd(n-1)}^{*} + k_{pd}\{V_{dcer(n)} - V_{dcer(n-1)}\} + k_{id} V_{dcer(n)} \text{.....} (4.20)$$

Where, K_{pd} and K_{id} are respectively proportional and Integral constants of the DC bus PI controller.

The in-phase components of the SLCVC reference currents are estimated as:

$$i^*_{cad} = I^*_{cmd} u_a$$

$$i^*_{cbd} = I^*_{cmd} u_b$$

$$i^*_{ccd} = I^*_{cmd} u_c \quad \ldots\ldots\ldots \quad (4.21)$$

The total SLCVC currents estimated by

$$i^*_{ca} = i^*_{caq} + i^*_{cad}$$

$$i^*_{cb} = i^*_{cbq} + i^*_{cbd}$$

$$i^*_{cc} = i^*_{ccq} + i^*_{ccd} \quad \ldots\ldots\ldots \quad (4.22)$$

Hysteresis Current Controller

The ON/OFF switching pattern of the gate drive signals to the IGBTs generated from the hysteresis comparator is represented mathematically as:

$$i_{ca} < (i_{ca}^* - hb)$$

Switch S1 off and switch S4 on. SA=0

$$i_{ca} > (i_{ca}^* + hb)$$

Switch S1 on and switch S4 off. SA=1

$$i_{cb} < (i_{cb}^* - hb)$$

Switch S3 off and switch S6 on. SB=0

$$i_{cb} > (i_{cb}^* + hb)$$

Switch S3 on and switch S6 off. SB=1

$$i_{cc} < (i_{cc}^* - hb)$$

Switch S5 off and switch S2 on. SC=0

$$i_{cc} > (i_{cc}^{*} + hb)$$

Switch S5 on and switch s2 off, SC=1

The set of differential equations, define the mathematical model of the SEIG system with the SLCVC based voltage regulator in terms of eleven dependent variables with time as an independent variable. The ten dependent variables are

1 d-axis component of the stator current

2 q-axis component of the stator current

3 d-axis component of the rotor current

4 q-axis component of the rotor current

5 phase 'a' current of SLCVC

6 phase 'b' current of SLCVC

7 phase 'c' current of SLCVC

8 DC capacitor voltage

9 d-axis component of the charge in the shunt capacitor

10 q-axis component of the charge in the shunt capacitor

The effectiveness of the new voltage regulator in controlling the ac voltage of the SEIG system is simulated by solving the dynamic model equations using Runga-Kutta method of integration (appendix D). For the purpose of studying the response of SEIG system and to have the graphical representation of its behavior, the variation of different quantities, such as voltage at the SLCVC terminal, dc bus voltage,

compensator currents are obtained. The machine used for this investigation is a 3.7 kw y-connected induction machine (ratings in Appendix B).

Voltage regulation of the SEIG system with the action of SLCVC based voltage regulator are studied for the following conditions:

1 voltage regulation at full load

2 voltage regulation during the removal of load

4.4 Results and Discussion

The results obtained through the digital simulation of the developed mathematical model highlighting the effectiveness of the SLCVC based voltage regulator to control terminal voltage of SLCVC.

4.4.1 Voltage control at full load

To study the effect of SLCVC based voltage regulator at full-load condition, the generator is started by the excitation capacitance of per phase value 53.44 microFarads. It is accelerated at the rate of 78 rad/sec ^{2} up to 1500 r.p.m. The capacitor supplies the average reactive power at the normal condition (Fig. 4.2, 4.3). The SLCVC is initially not switched on. After the voltage attains a steady state value the SLCVC control scheme is brought into operation. The SLCVC capacitor is initially charged at 525 V before starting the switching operation. The

Fig 4·2 Vm vs T curve before SLCVC is switched on

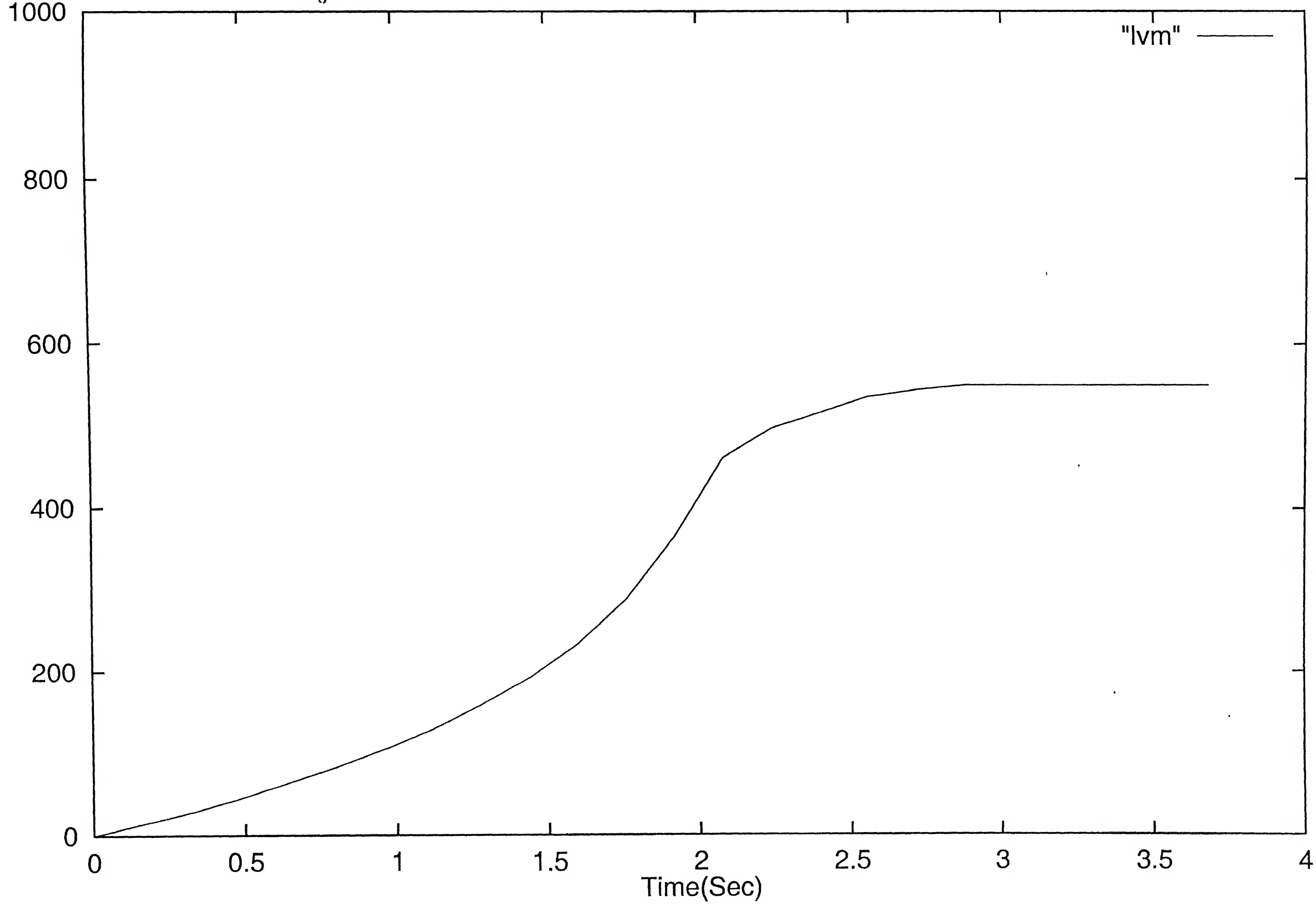
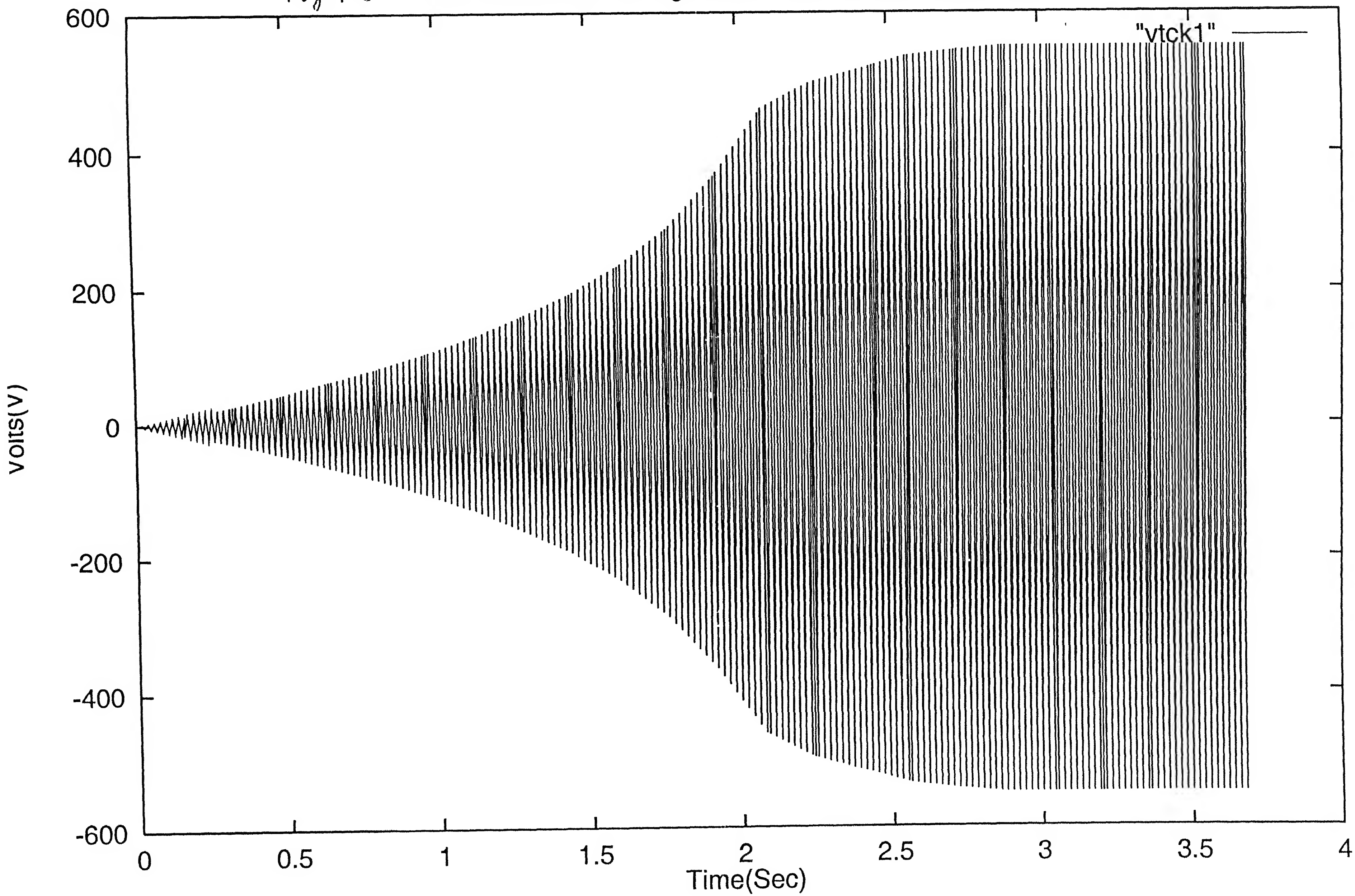


Fig 4·3 The instaneous voltage before the SLCVC turned on



capacitor can be charged by the SEIG system after it attains the steady-state voltage (which is possible due to the anti-parallel diode across the IGBT).

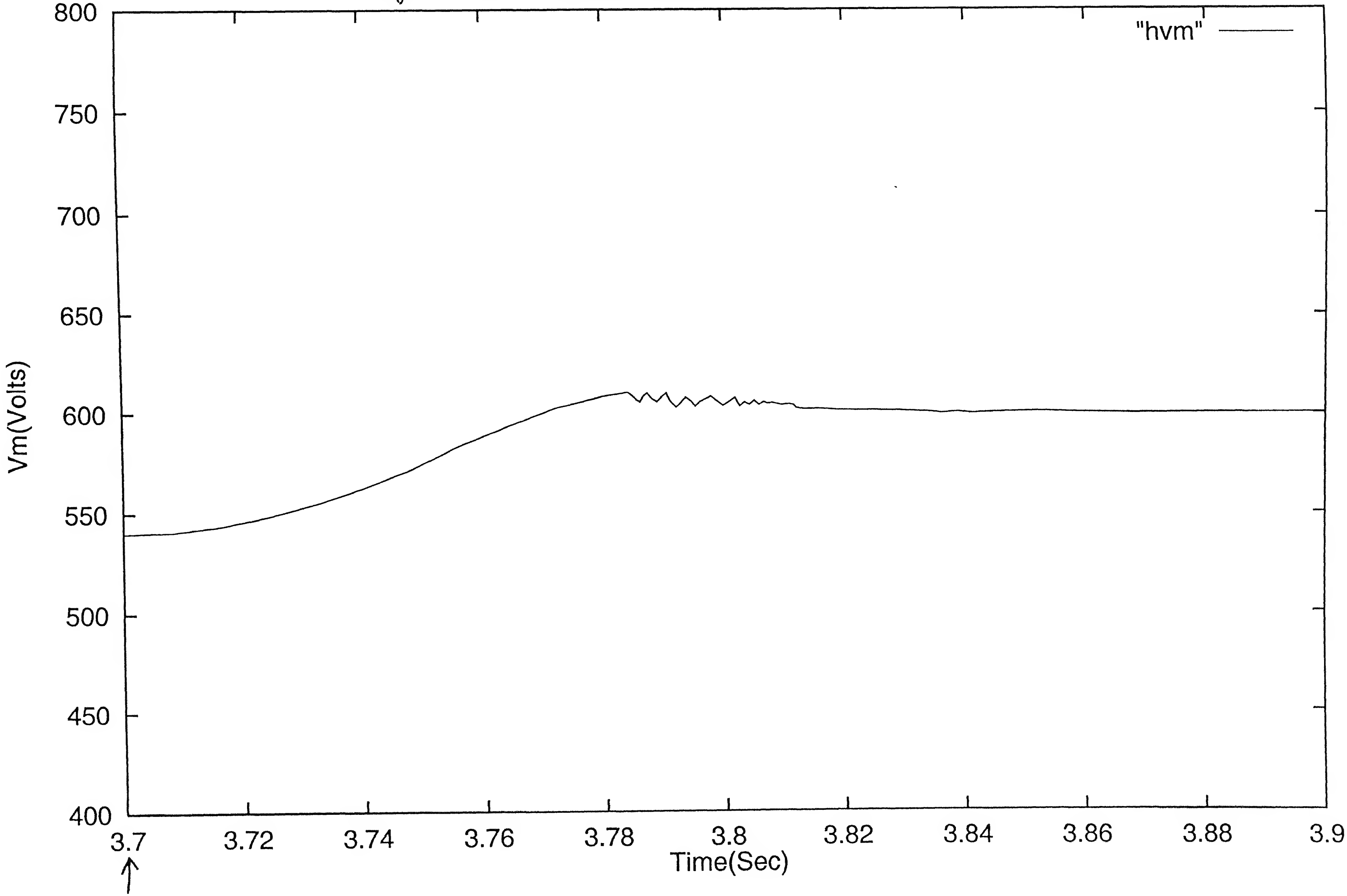
The voltage of the generator during build-up settles to 550V(r.m.s 388.9V). However, the DC voltage is not at reference voltage set at 700V, which is required for the adequate control of SLCVC. When the SLCVC is started in its normal operation as inverter (at time 3.7 s), the terminal voltage builds up to 600V(r.m.s 425V) and the voltage of the DC bus of SLCVC is regulated to reference level in 88 ms (Fig. 4.4-4.7).

When the SLCVC comes into operation it starts to operate in capacitive mode where the current leads the voltage by 90 degrees at steady-state. There is a rush of current in order to regulate the voltage to desired reference voltage. There is a small oscillation in the ac voltage, which is possible to be minimized by optimum selection of PI controller parameters. The dc bus voltage smoothly regulated to a reference level.

4.4.2 Voltage Control with removal of load

The objective of the voltage regulator is to regulate the terminal voltage of the generator with load. The effectiveness of the proposed voltage regulator in controlling the terminal voltage of three-phase SEIG is evaluated by removal of load of 1.5 kw. The load is removed at time of 4.5 second in a condition when the SLCVC is already in operation (Fig. 4.8-4.11). The generator peak voltage experiences a small excursion at the instant of load switching and the

Fig 4·4 Vm vs t curve after SLCVC is switched on



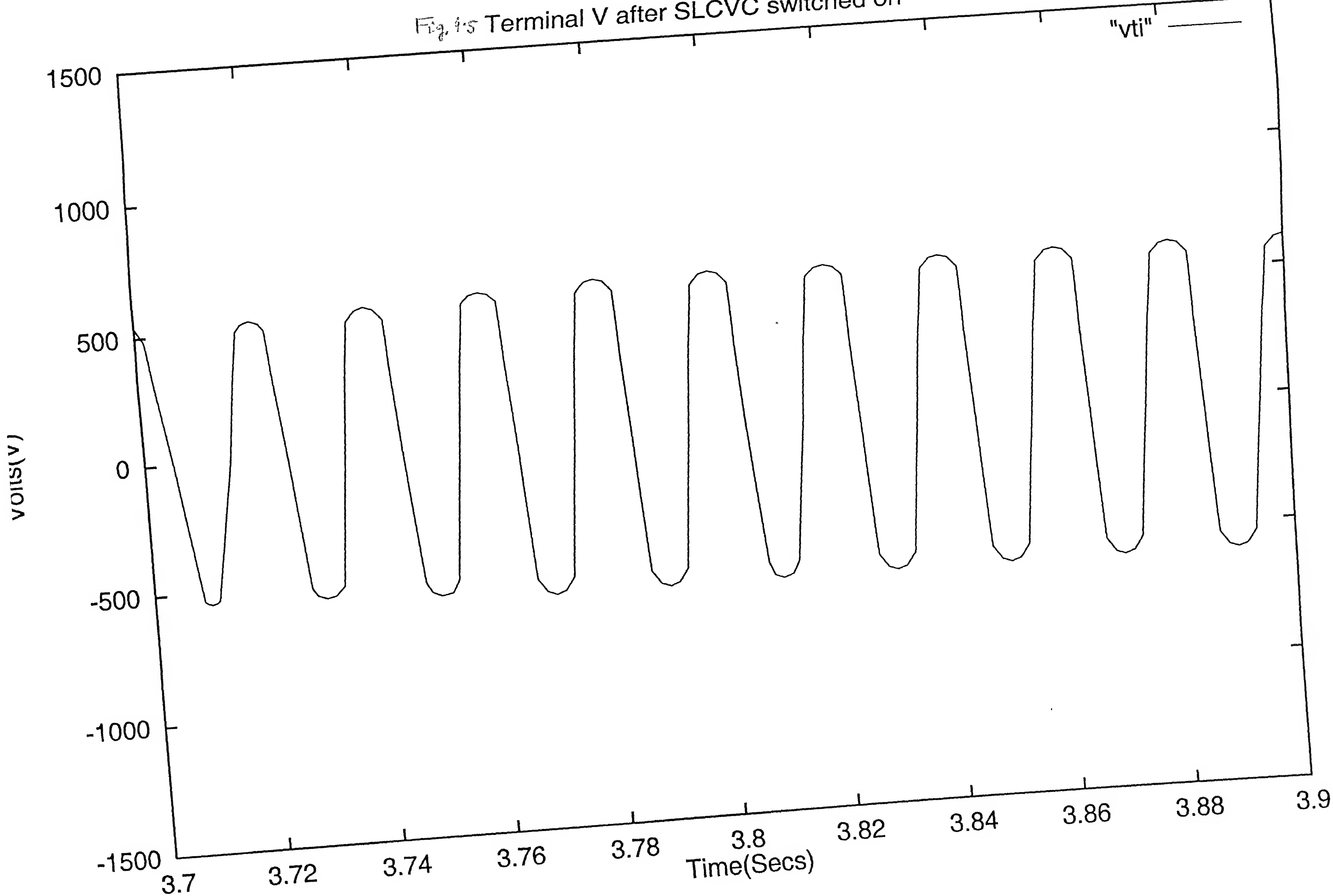


Fig. 1.5 Terminal V after SLCVC switched on

Fig 4·6 SLCVC Current after switch is turned on

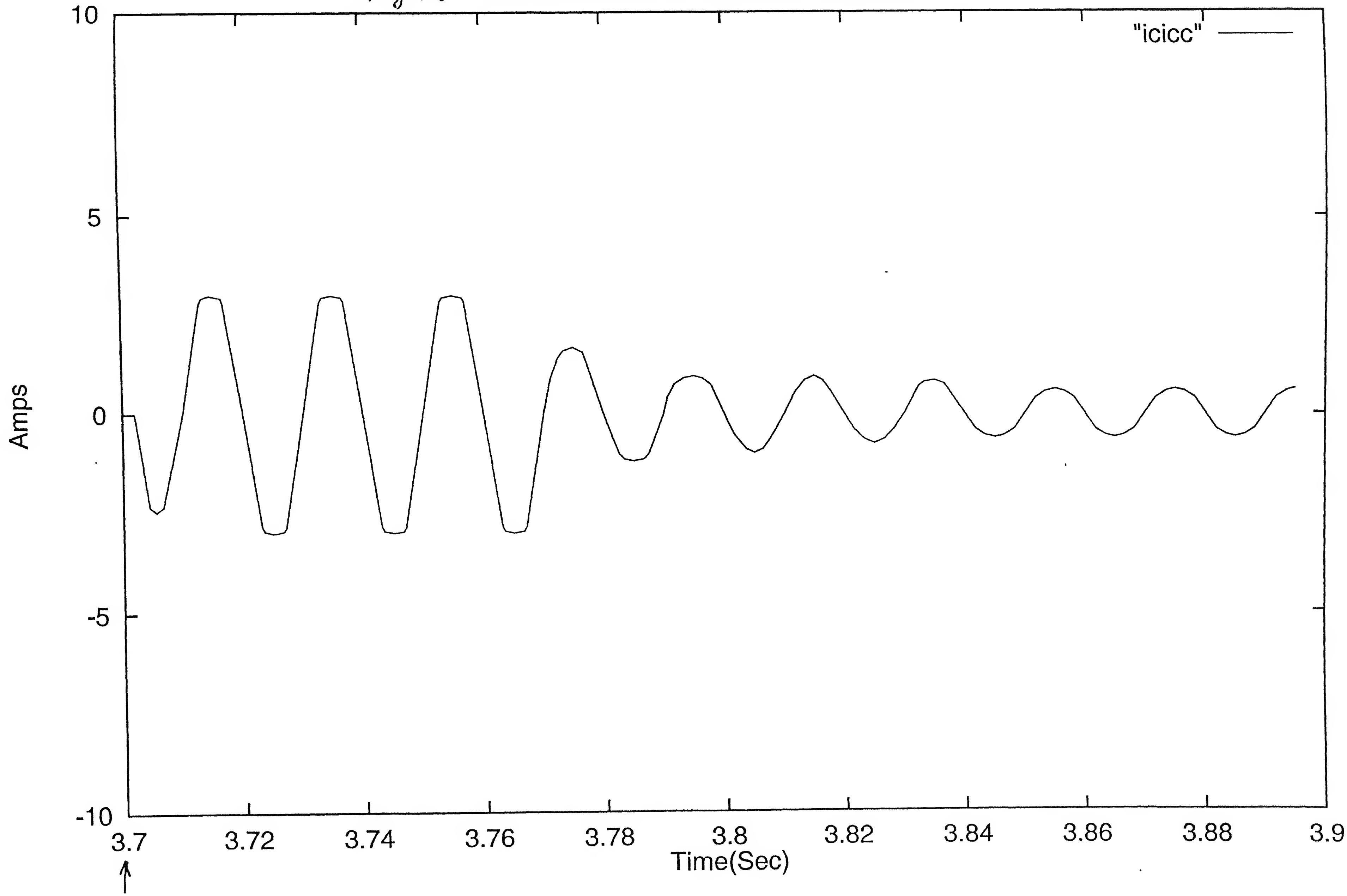


Fig.4.7 DC capacitor voltage after SLCVC is turned on

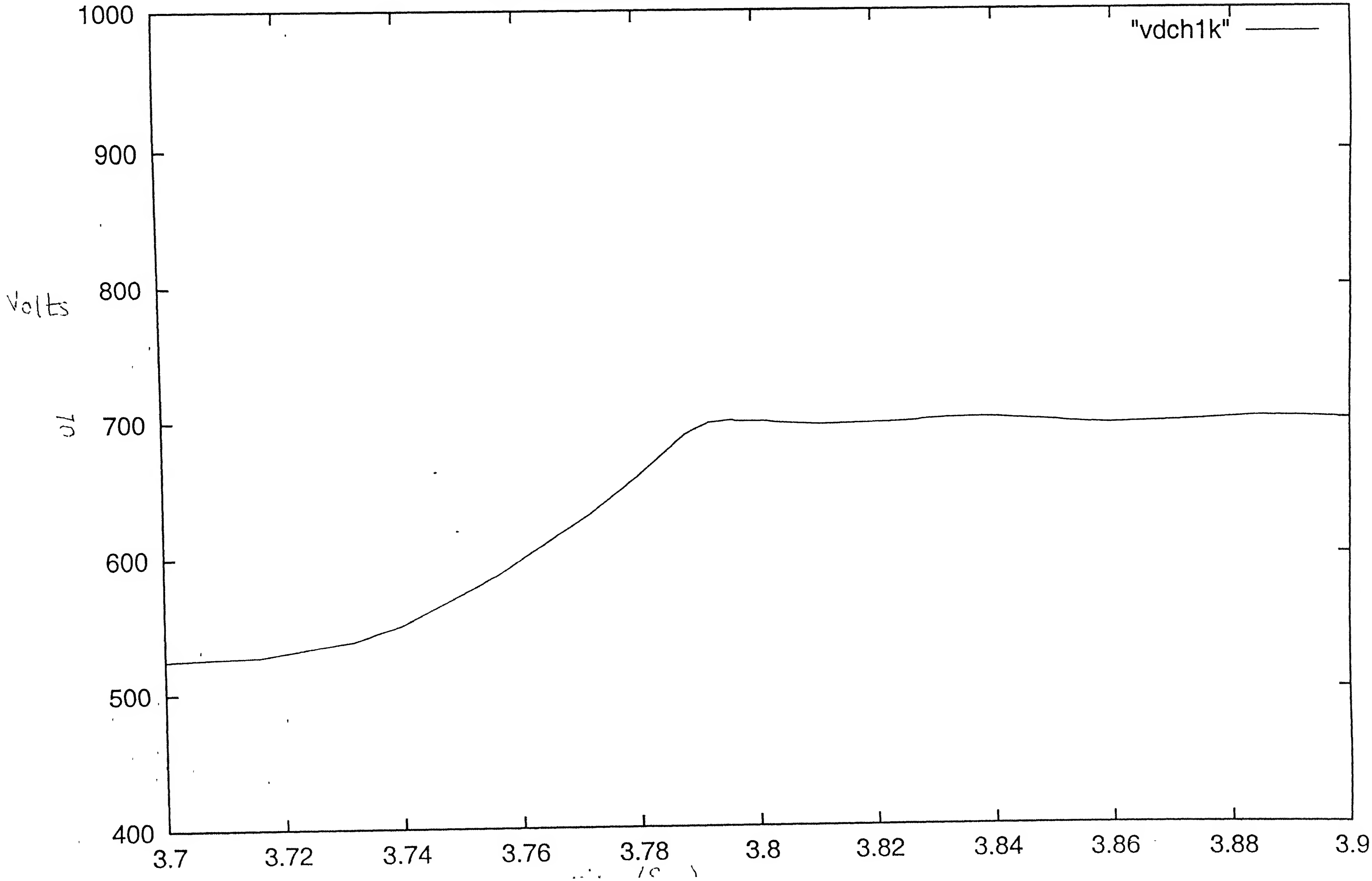


Fig 4.8 Vm after load is reduced

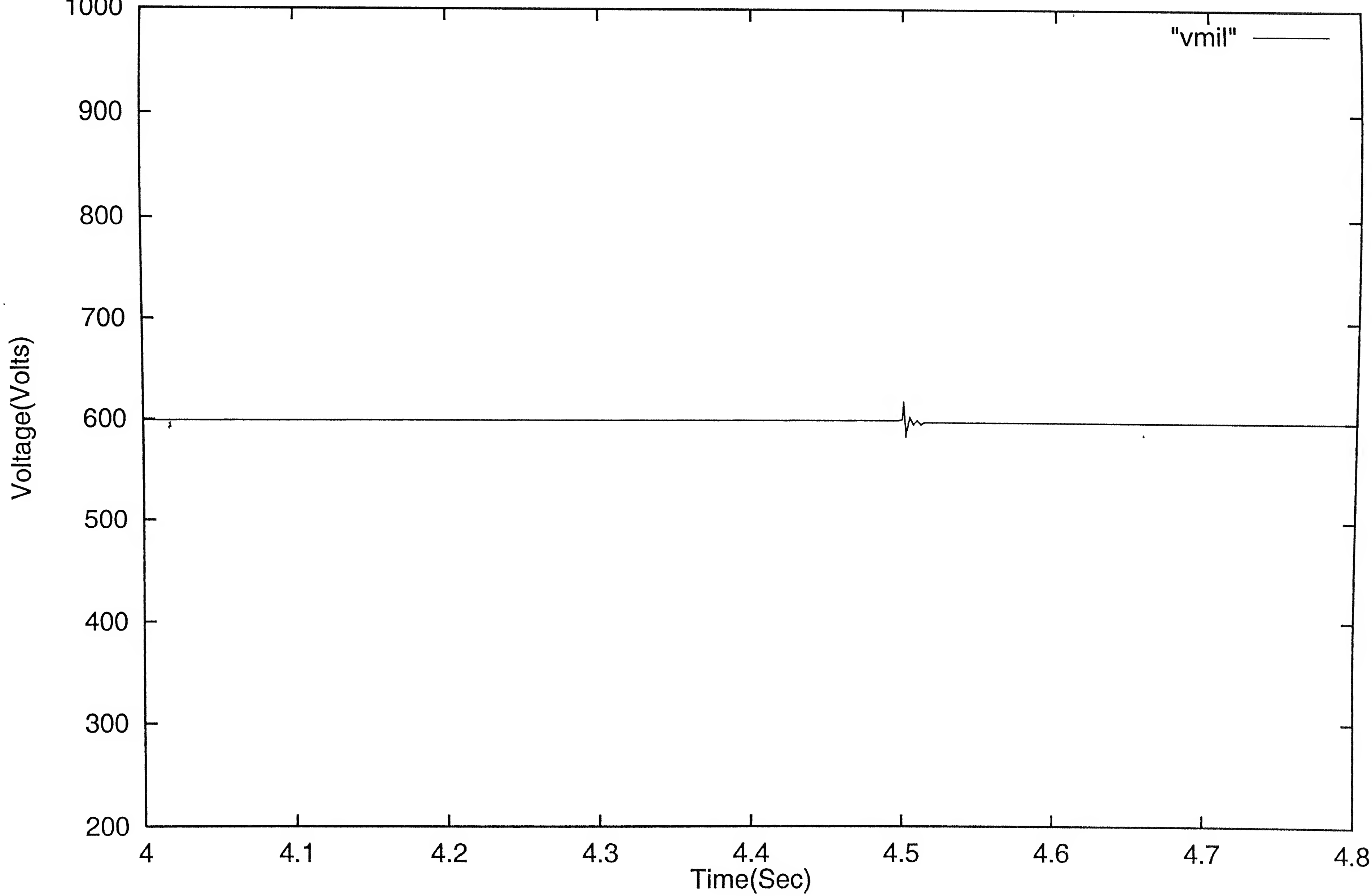


Fig4.9 instaneous current after the load is reduced

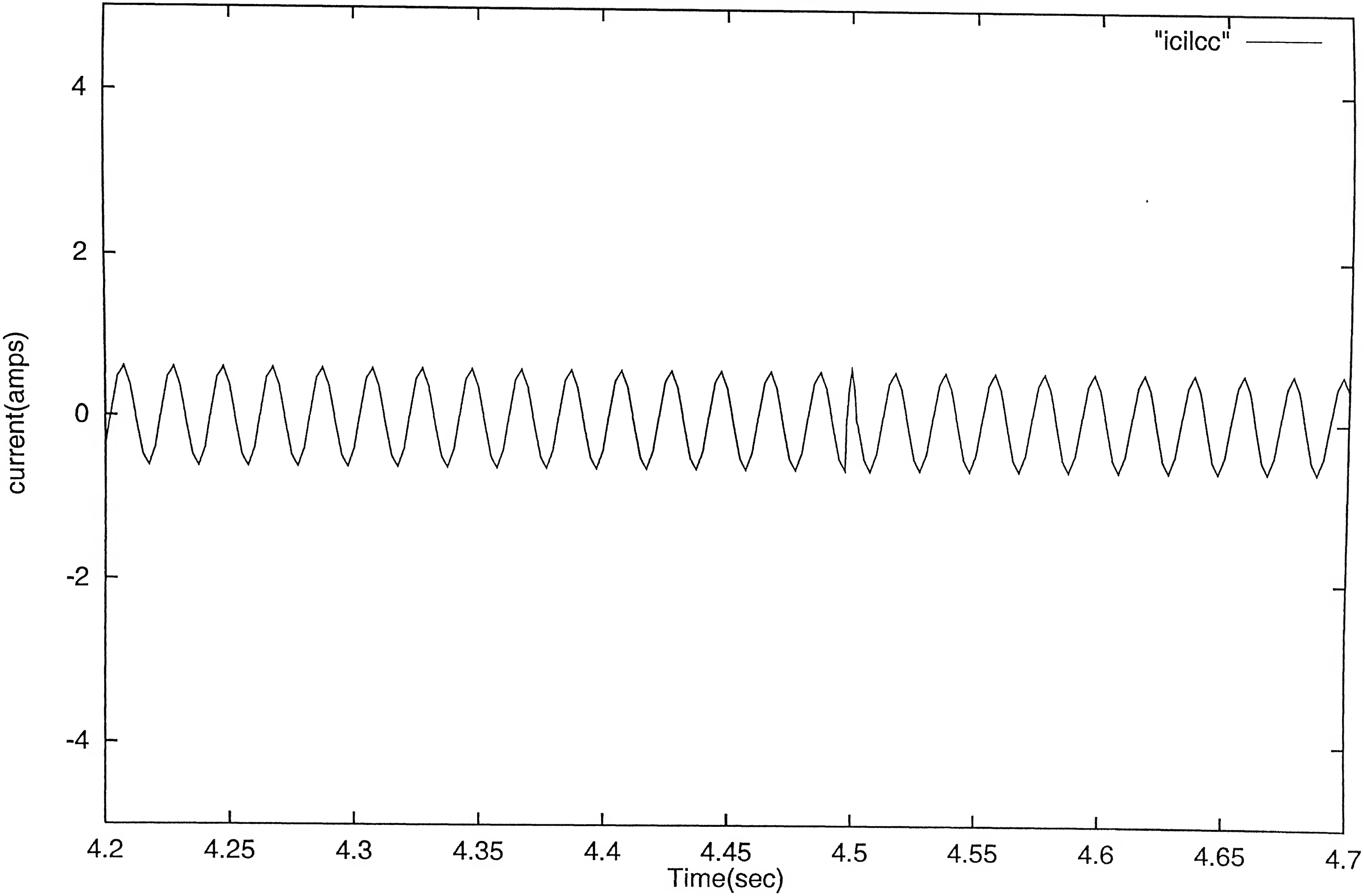


Fig 4·10 Effect of load change on DC voltage

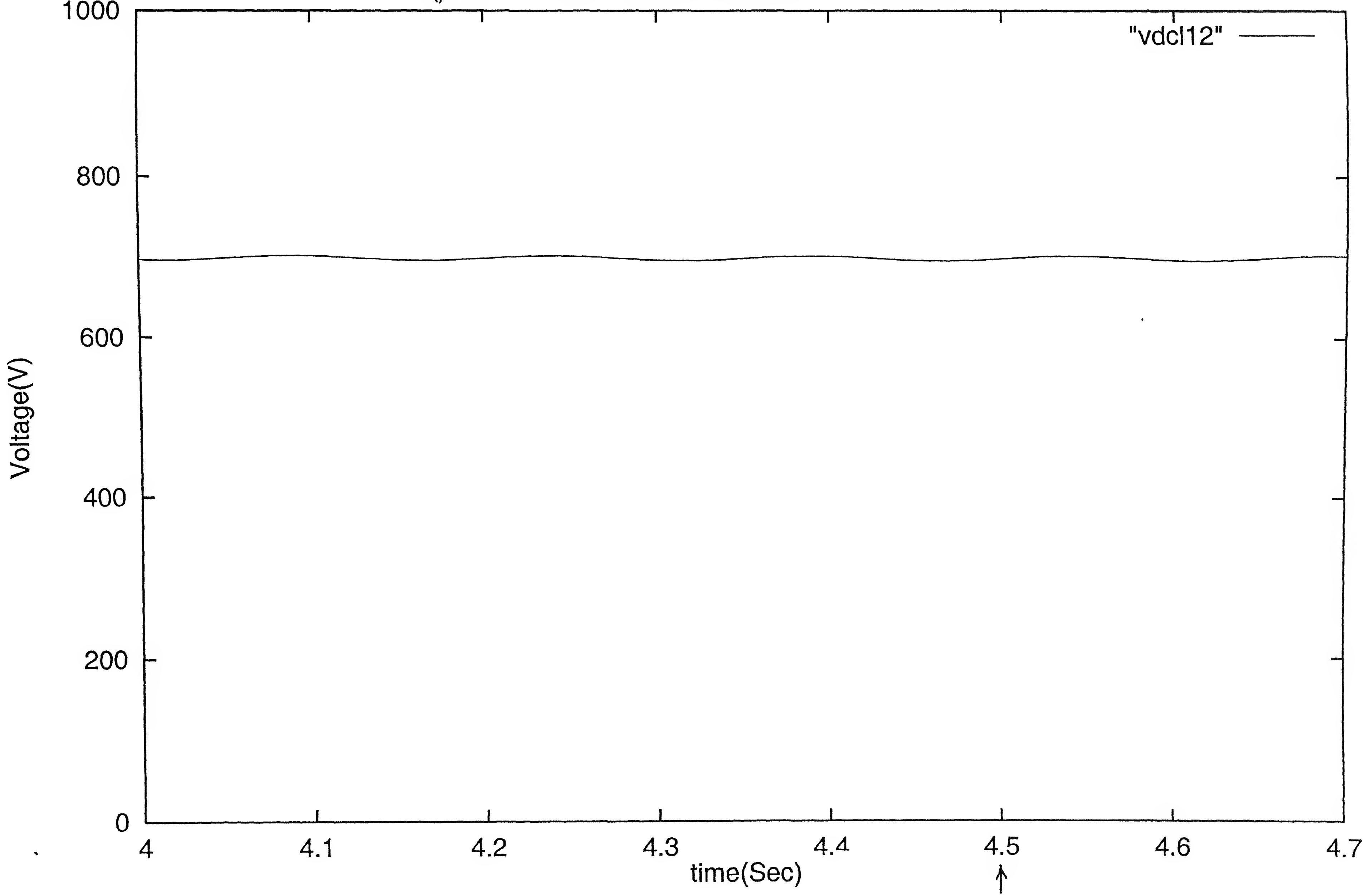
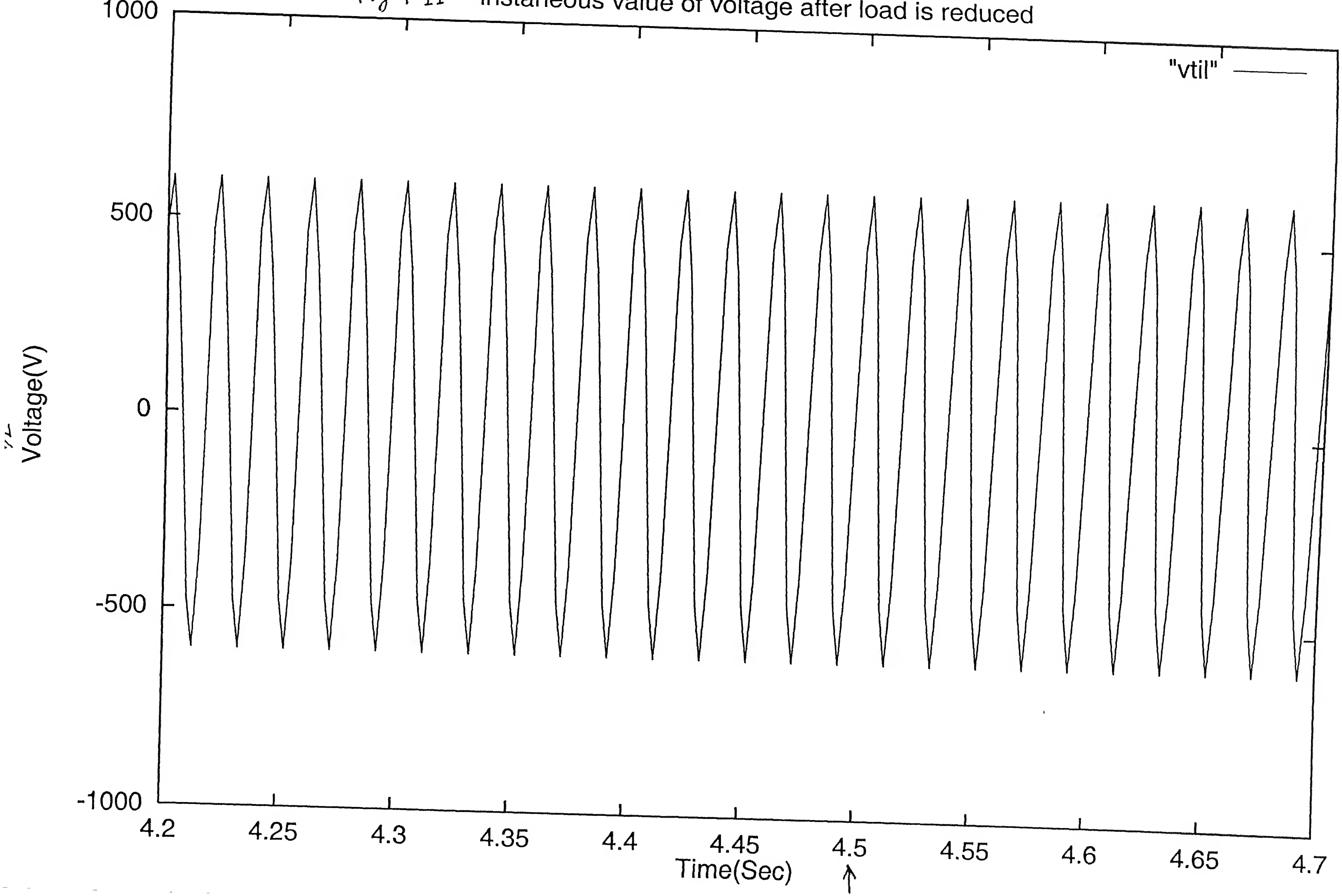


Fig 4·11 instaneous value of voltage after load is reduced



instantaneous value of the SEIG terminal voltage remains stable at a level of 600V. There is a remarkable phase shift of 180 degree. Now the SLCVC consumes a reactive current to regulate the terminal voltage. The DC voltage of the SLCVC remains almost constant.

4.5 Conclusion

The SLCVC based voltage regulator provides to the SEIG a desirable feature of synchronous converter operating in inductive and capacitive modes. The use of SLCVC helps the SEIG to save from de-excitation during the severe condition of load change. It has a faster dynamic response for regulating the voltage. The voltage-regulating scheme is adaptive to the changing load condition and hence it is possible to operate the SEIG at almost constant voltage at a wide range of load variation.

As the proposed solid-state regulator is capable of generating both the capacitive as well as inductive current, the large ac capacitor and inductor banks with their associated switchgear and protection, used in conventional SVCs, are not needed. This results in a significant reduction in size and makes it applicable in isolated power system at remote places.

The requirement of digital processor and controller circuit increases the cost of the SEIG scheme. However, the advantages of improved dynamic performance and the reliability of the SEIG scheme

with the proposed voltage regulator outweigh this added cost. The implementation of the SLCVC based voltage regulator in the SEIG system will reinforces the technology of small power generation from non-conventional sources of energy.

CHAPTER 5

STEADY-STATE ANALYSIS OF SINGLE-PHASE SELF-EXCITED INDUCTION GENERATOR

5.1 Introduction

The capacitor self-excited induction generator is becoming popular for generating electrical power from unconventional energy sources like wind, bio-gas, small hydro-heads etc. It is due to its numerous advantages over conventional synchronous generator such as brush-less construction with cage rotor, reduced size, no separate DC source excitation, least maintenance and above all low cost. Moreover, simple means are needed to maintain the terminal voltage at a desired level at a desired speed. These are done, by providing an excitation capacitance across the generator terminal. For the design of voltage regulating system, the knowledge of machine performance and capacitive VAR requirement to maintain the terminal voltage constant, are needed.

A large number of attempts have been made to analyze the performance of 3-phase capacitor excited induction generators. But, not much has been done on the analysis of single-phase capacitor-excited induction generator. It is of much interest because of its various small-scale applications such as emergency supply, low level power generation for lighting at remote and isolated places and a portable source of power supply at construction sites etc.

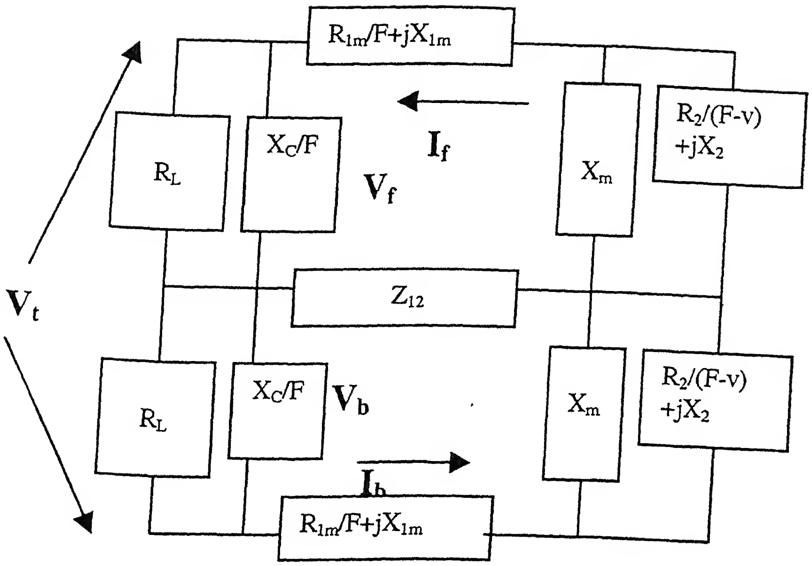
An attempt is, therefore, made in this chapter to analyze the steady-state performance of capacitor self-excited single-phase induction generator. An analytical technique is used to determine the excitation requirement to maintain the voltage at desired level at a desired speed. The technique uses a standard equivalent circuit to obtain non-linear algebraic equations in terms of unknown parameters and the Newton-Raphson method is used to solve them. Different effects are also studied on generator performance, which would provide the proper guidelines for the design of a regulating and converting systems.

5.2 Analysis

In this analysis it is assumed that all the machine parameters other than the magnetizing reactance are not affected by magnetic saturation. The effect of space harmonics, the time harmonics in the induced voltage and the core losses are ignored. A resistive load is considered.

The steady-state equivalent circuit [28] of a single-phase capacitor excited Induction Generator is shown in Figure5.1. In which, R_1 and R_2 are the resistances of stator and rotor referred to the stator, respectively. X_1 and X_2 are the leakage reactances of the stator and rotor referred to the stator, respectively. The X_m is the magnetizing reactance and X_C is the reactance of the terminal capacitance 'C'. R_L is the load resistance, and F and v are per unit speed and frequency respectively.

Analytical technique for performance analysis



I_1=Loop current when Z_{12} is open

Fig5.1. Equivalent circuit of single phase Induction generator

Here in this topology the load is connected across the main winding. Because isolated induction generators are characterized by their operation at variable frequencies, rated per phase magnetizing reactance has been adjusted for the suitable per unit operating frequency, F. Also, the per unit rotor speed has been used in place of the slip. The relation between the symmetric component voltage and currents shown in the equivalent circuit and the actual voltage and currents are as follow:

$$\begin{pmatrix} V_m \\ V_a \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ jk & jk \end{pmatrix} \begin{pmatrix} V_f \\ V_b \end{pmatrix} \quad (5.1)$$

$$\begin{pmatrix} I_m \\ I_a \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ j/k & -j/k \end{pmatrix} \begin{pmatrix} I_f \\ I_b \end{pmatrix} \quad (5.2)$$

Where the subscripts 'a' and m refer to the stator auxiliary and main windings respectively, and f and b refer to the forward and backward symmetrical components, respectively, and k is the winding ratio. The two loop equations of the equivalent circuit are:

$$\begin{pmatrix} V_f / F \\ V_b / F \end{pmatrix} = \begin{pmatrix} Z_{11} & -Z_{12} \\ -Z_{12} & Z_{22} \end{pmatrix} \begin{pmatrix} I_f \\ I_b \end{pmatrix} \quad (5.3)$$

Where

Z_f and Z_b are the forward and backward impedance respectively.

$$Z_{11} = Z_{1m}/2 + \frac{Z_{1a}}{2k^2} + Z_f \text{......} (5.4)$$

$$Z_{22} = \frac{Z_{1m}}{2} + \frac{Z_{1a}}{2K^2} + Z_b \text{......} (5.5)$$

$$Z_{12} = \frac{1}{2}\left(\frac{Z_{1a}}{k^2} - Z_{1m}\right) \text{......} (5.6)$$

$$Z_{1m} = \frac{R_{1m}}{F} + jX_m \text{......} (5.7)$$

$$Z_{1a} = \frac{R_{1a}}{F} + jX_{1a} - \frac{jX_c}{F^2} \text{......} (5.8)$$

$$Z_f = \frac{jX_m(R_2/(F-v) + jX_2)}{R_2/(F-v) + j(X_m + X_2)} \text{......} (5.9)$$

$$Z_b = (jX_m(R_2/(F+v) + jX_2))/(R_2/(F+v) + j(X_m + X_2)) \text{......} (5.10)$$

$V_f = V_b = V_m/2$........(5.11)

Substitution from (5.4) through (5.6) into (5.3) gives

$$\frac{I_f}{I_b} = \frac{Z_{1a}/k^2 + Z_f}{Z_{1a}/k^2 + Z_b} \text{......} (5.12)$$

The load is connected to the terminal of the main winding. The load is resistive. From (5.4) it can be seen that :

$$V_f = V_m/2 = -Z(I_f + I_b)/2 \text{......} (5.13)$$

The negative sign indicates the generating mode. Substituting for V_f in (5.3) gives:

$$\frac{I_f}{I_b} = \frac{Z_{12} - Z/2F}{Z_{11} + Z/2F} \qquad (5.14)$$

Now in our case, we consider that the auxiliary circuit is open. From fig5.1 we see that the loop impedance for the stator current may be written as

$$Z_T I_1 = 0 \qquad (5.15)$$

Equating the real and imaginary parts of the loop impedance (Z_T) zero, we get two non-linear equations as follows:

$$\begin{aligned} f(F, X_m) &= (C_1 + C_2 X_m + C_3 X_m^2) F^4 + \\ &(C_4 + C_5 X_m + C_6 X_m^2) F^2 + \\ &(C_7 + C_8 X_m + C_9 X_m^2) \qquad (5.16) \end{aligned}$$

$$\begin{aligned} g(F, X_m) &= (D_1 + D_2 X_m + D_3 X_m^2) F^3 + \\ &(D_4 + D_5 X_m + D_6 X_m^2) F^2 + \\ &(D_7 + D_8 X_m + D_9 X_m^2 F +) \\ &(D_{10} + D_{11} X_m + D_{12} X_m^2) \qquad (5.17) \end{aligned}$$

Where the coefficients C are:

$$C_1 = R_L X_1 X_2^2$$
$$C_2 = R_L X_2 (X_2 + 2X_1)$$
$$C_3 = R_L (X_2 + X_1)$$
$$C_4 = -X_C X_2^2 (R_L + R_1) + 4X_C X_2 X_1 R_1 + R_L R_2^2 (X_1 + X_2)$$
$$-2R_1 R_2 X_2 R_L - v^2 R_L X_1 X_2^2$$
$$C_5 = -2X_C X_2 (R_L + R_1) - X_C (2R_1 X_1 + R_2) + 2X_C X_2 R_2$$
$$-2R_1 R_2 R_L - v^2 X_2^2 R_L - 2v^2 R_L X_1 X_2$$
$$C_6 = -X_C (R_L + R_1) - v^2 R_L R_1 - v^2 X_C X_2$$
$$C_7 = (R_L + R_1)(X_C R_2^2 + v^2 X_2^2)$$
$$C_8 = 2v^2 X_2 (R_L + R_1)$$
$$C_9 = v^2 (R_L + R_1)$$

And the coefficients d are:

$$D_1 = -R_L R_2 X_1 X_2$$
$$D_2 = -X_c X_2^2 - R_L R_2 (X_2 + 2X_1)$$
$$D_3 = -R_L R_2 + X_C X_2$$
$$D_4 = -X_C X_1 X_2^2 - R_L R_1 X_2^2$$
$$D_5 = -2X_C X_1 X_2 - 2R_L R_1 X_2$$
$$D_6 = -X_C X_1 - R_L R_1$$
$$D_7 = 2X_C X_2 R_2 (R_L + R_1)$$
$$D_8 = X_C (2R_2 (R_1 + R_L) + v^2 X_2^2 + R_2^2)$$
$$D_9 = -v^2 X_2 X_C$$
$$D_{10} = X_C X_1 R_2^2 + v^2 X_2^2 X_1 X_C + R_1 R_L R_2^2 + v^2 R_1 R_L X_2$$
$$D_{11} = 2v^2 X_1 X_2 X_C + v^2 R_1 R_L$$
$$D_{12} = v^2 X_1 X_C$$
$$Z_1 = R_1 + jFX_1$$
$$Z_L = R_L(-jX_C / F) / (R_L - jX_C / F)$$

The relationship between the air-gap voltage and terminal voltage is (auxiliary circuit open and load directly connected across the main winding):

$$V_g = V_T(1 + Z_L / Z_1)$$

The solution of the two non-linear simultaneous equations can be obtained by various numerical techniques, when the initial guess for the values F and X_m are provided. Newton-Raphson method has been used to determine the values of F and X_m for a given speed, excitation capacitance and load impedance. The magnetization curve of the main winding can be then used to get the air-gap voltages. Calculating, the terminal voltage from the terminal voltage-air-gap voltage relation the performance indices can be calculated.

The magnetizing characteristics are approximated to be:

$$V_{gm} / F = K_1 - K_2 X_m \quad \text{..........} \quad \text{.........(}5.18\text{)}$$

$$V_{ga} / F = K_1 - K_2 X_m \quad \text{..........} \quad \text{.........(}5.19\text{)}$$

Where k_1 and k_2 are constants which depend upon the design of the machine.

Analytical Technique for Constant Voltage

In this section, the analysis for the generator performance to maintain constant terminal voltage at different values of load at given

speed is presented. The terminal voltage, in the case of Induction generator at given load and speed, may be easily maintained by connecting a capacitor of variable value. The same equivalent circuit is used but here X_C and F are unknown.

The two equations that are used are modified form of (5.16) and (5.17)

$$f(X_C,F)=F^4C_1+F^2(X_CC_2+C_3)+X_CC_4=0 \quad \text{.......(5.20)}$$

$$g(X_C,F)=F^3(X_CD_1+D_2)+F^2(X_CD_3+D_4)+FX_cD_5+X_CD_6+D_7=0 \quad (5.21)$$

Where the constants are defined as:

$$C_1 = R_LX_mX_2(X_m+X_2)+R_LX_1(X_m+X_2)^2$$
$$C_2 = -(X_m+X_2)^2(R_L+R_1)-(X_m+2X_2)(2R_1X_1+X_mR_2)$$
$$C_3 = R_LR_2^2(X_1+X_2)-(X_m+X_2)(2R_1R_2+v^2X_mX_2)R_L-v^2R_LX_1(X_m+X_2)^2$$
$$C_4 = R_2^2(R_L+R_1)+v^2(X_m+X_2)^2(R_L+R_1)$$
$$D_1 = -X_mX_2(X_m+X_2)$$
$$D_2 = -R_LR_2(2X_1+X_m)(X_m+X_2)$$
$$D_3 = -X_1(X_m+X_2)^2$$
$$D_4 = -R_1R_L(X_m+X_2)^2$$
$$D_5 = (X_m+X_2)(2R_LR_2+2R_1R_2+v^2X_mX_2)+X_mR_2^2$$
$$D_6 = X_1R_2^2+$$
$$v^2X_1(X_m+X_2)^2$$
$$D_7 = v^2R_1R_L(X_m+X_2)+R_1R_LR_2^2 \quad \text{.......(5.22)}$$

The Newton-Raphson method needs initial guess of unknown variables, say X_{CO} and F_O. Generally the initial values are taken as:

F_O = v and X_{CO} = X_{mr}=rated magnetizing reactance...(5.23)

The equation (5.22) contains all terms of machine parameters, load resistance and speed. The flow-chart of the computational technique is same as given in the three-phase case.

For the assumed guess values of X_C and F, the V_g (air-gap voltage) can be calculated for a given terminal voltage, which is to be maintained to be constant. Now corresponding to the V_g magnetizing reactance is calculated by the magnetization curve. At the end of the first iteration of method, X_C and F will have incremented values. The increments are computed by:

$$\begin{pmatrix} \Delta X_C \\ \Delta F \end{pmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}^{-1} \begin{bmatrix} -f_o \\ -g_o \end{bmatrix} \qquad (5.24)$$

Where the Jacobian elements $J_{11}, J_{12}, J_{21}, J_{22}$ can be computed as:

$$J_{11} = \Delta f / \Delta X_C$$
$$J_{12} = \Delta f / \Delta F$$
$$J_{21} = \Delta g / \Delta X_C$$
$$J_{22} = \Delta g / \Delta F$$

All these equations are in partial differential form.

f_o and g_o are the values of the equations (5.20) and (5.21) for the initial values of Xc and F. The iterative process may continue till the convergence criterion can be satisfied i.e. when |f(Xc, F)|<epsilon and |g(Xc, F)|<epsilon , where epsilon is very small quantity as per desired

accuracy. The algorithm technique for analysis is same as that developed in three-phase case.

Having obtained X_C and F for constant terminal voltage, the other machine performance parameters may be computed from equivalent circuit as follows (Z_L is the parallel combination of load and capacitor, divided by per unit frequency)

$$P_O = V_t^2 / R_L; \qquad Q_C = V_t(I_1 - I_L); \qquad I_1 = V_t / Z_L$$

5.3 RESULTS AND DISCUSSION

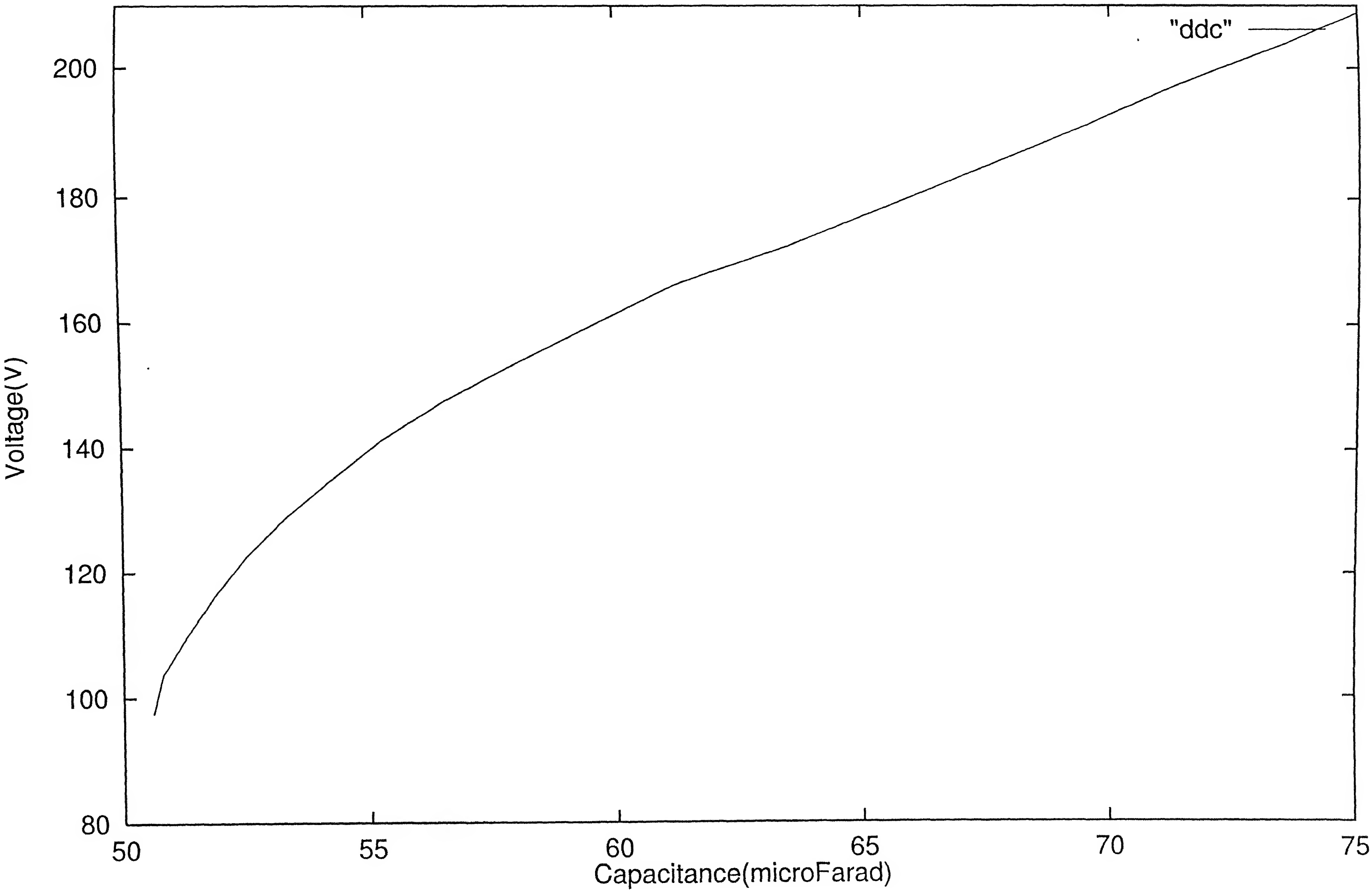
The performance characteristics of a capacitor excited, 2.5KW, cage generator are obtained (ratings given in appendix C). From the results these salient features are observed.

(1) The full load characteristic of the machine (Fig.5.2) shows that the terminal voltage of the machine increases with increase in capacitance and the rise of voltage is limited by the saturation of the magnetic circuit of the machine. Decrease in capacitance reduces the terminal voltage till capacitance is equal to the critical capacitance (below which the machine loses excitation).

(2) The variation of reactive power (VAR) with output power for rated terminal voltage is also computed (Fig.5.3-5.4). The load is varied between 2.5kw and 1.7kw at rated speed. For constant terminal voltage, the value of VAR increases with output power. In our proposed scheme a fixed valued capacitor is connected in shunt to the SEIG system. It supplies a VAR, which is the average of the VAR requirements at 1.7kw and 2.5kw. The calculated value of capacitance is 58.4 micro-farad. The rest of the reactive power is supplied or consumed by the SLCVC. The result shows that the SLCVC operates at both inductive and capacitive modes. It also shows that, for an increase in output power of the machine at rated speed, the reactive power has to vary continuously for regulating the machine terminal voltage.

(3) For a variable speed prime-mover, the effect of speed on the excitation requirements by the machine is also studied (fig.5.5-5.8). The variation of speed with reactive power requirement to maintain

Fig.5.2 Capacitance vs Voltage curve for single phase



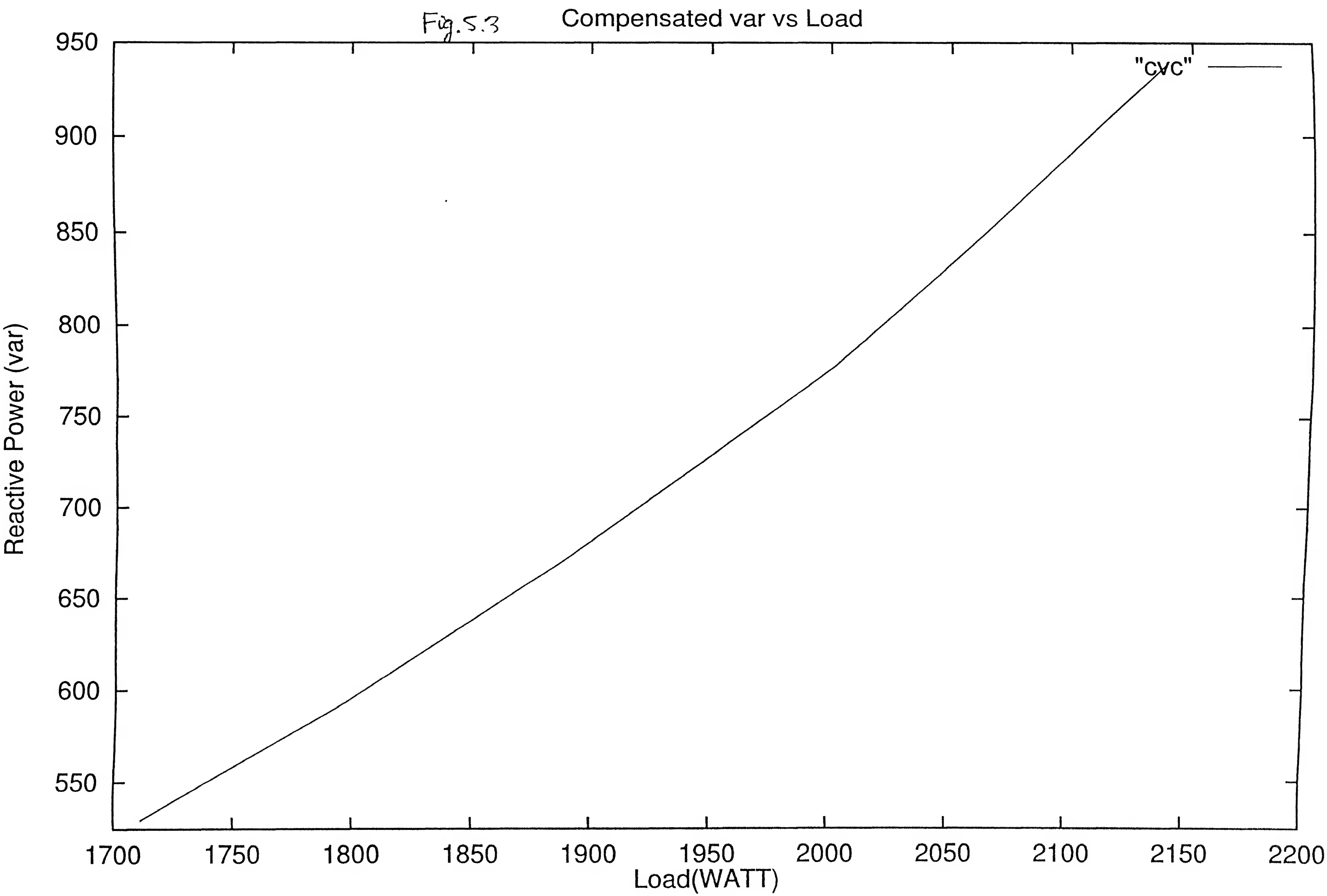

Compensated var vs Load
"cvc"
Reactive Power (var)
950
900
850
800
750
700
650
600
550
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
Load(WATT)

Fig.5.3

Fig.5.4 SLCVC VAR vs LOAD

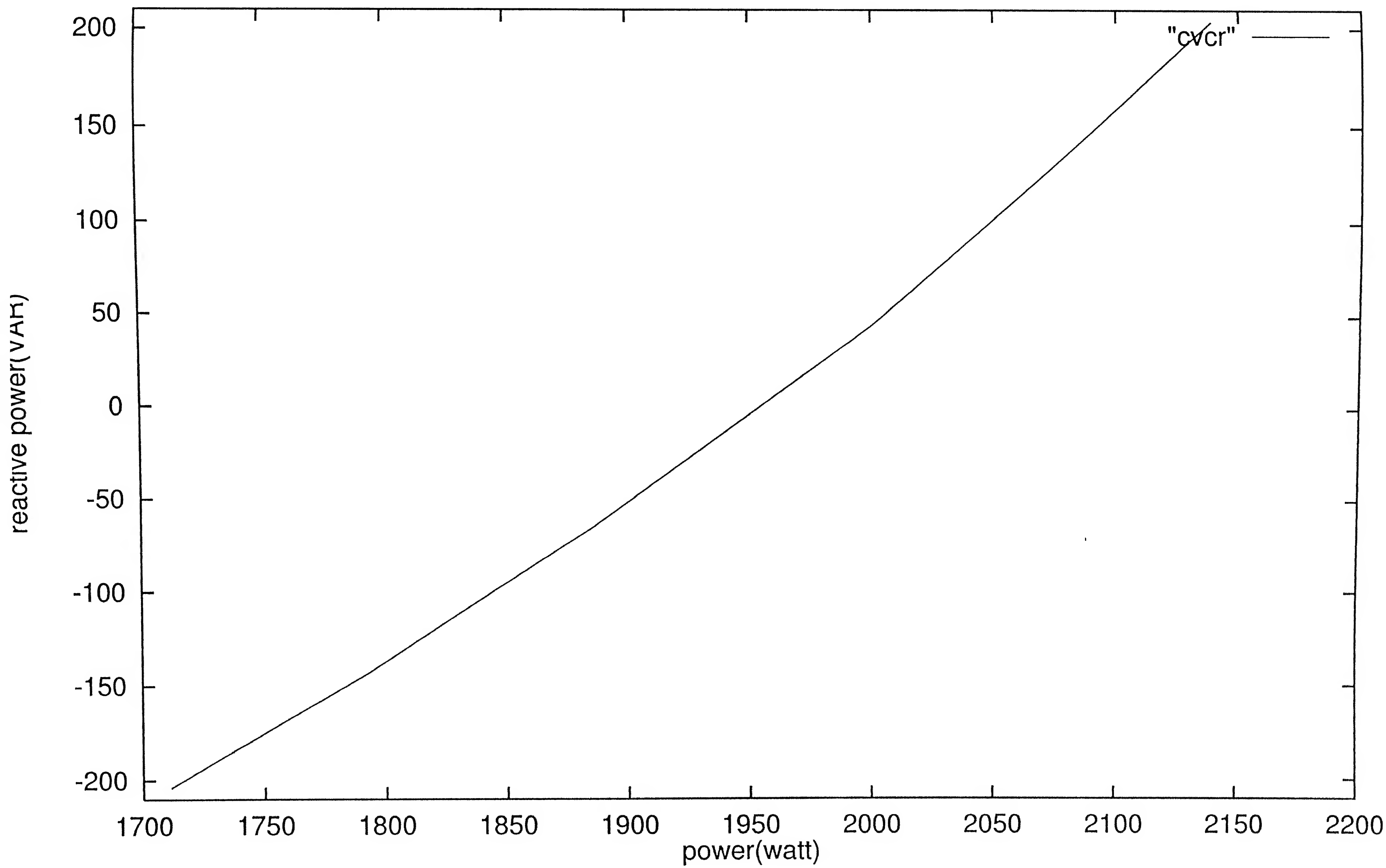


Fig 5·5 total reactive power(gen voltage const) at variable speed

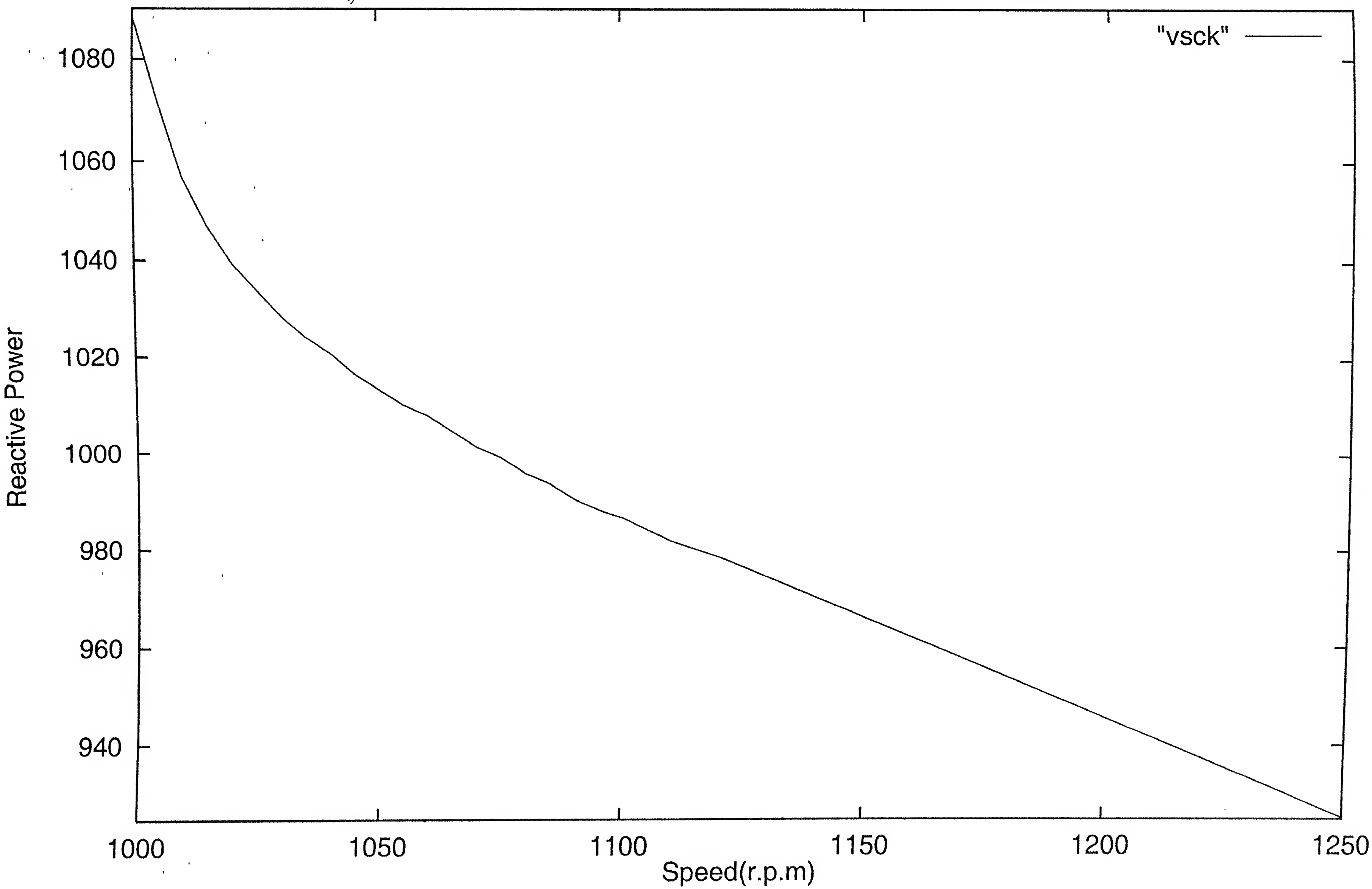
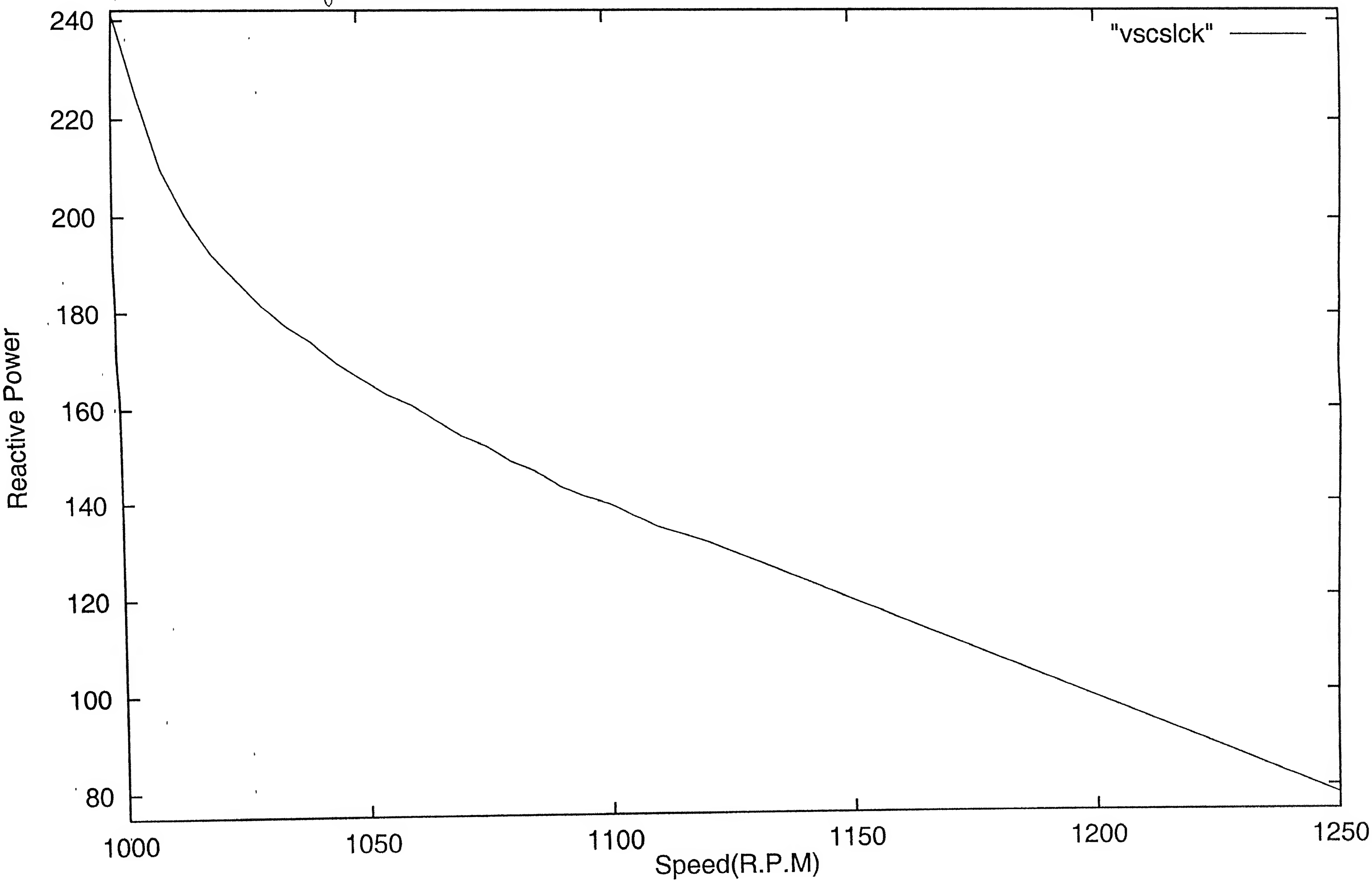


Fig 5 6 SLCVC generated VAR at variable speed(term volt const)



the terminal voltage constant at rated value under loaded condition of the machine is shown. There is a fixed capacitance in parallel with SLCVC. The rest of the inductive or capacitive reactive power is supplied by the SLCVC. The SLCVC acts as a variable capacitor or inductor. The computations are made both at 1.7kw and 2.5kw. It may be noted that the reactive power requirement reduces with the increase of speed. It may also be observed that the machine requires higher value of reactive power at full load compared to reduced load condition of the generator. It is seen from the frequency-power characteristics that the frequency is now nearer to 50 Hz compared to the case, when SLCVC was not used (Fig.5.9).

(4) The load characteristic of the machine in terms of terminal voltage and frequency with variation in output power for a value of capacitance of 58.4 micro-farad at rated speed, is also studied (Fig.5.10-5.11). The fall in voltage with increase in load, is observed due to effect of armature reaction, impedance drop and its dependent excitation. The characteristic shows that the machine behaves like a dc self excited generator with a resistance in the field winding. The increase of capacitance (over-excitation) also increases the output power, which should be stopped if the current exceeds its rated value.

5.4Conclusion

The performance characteristics of the machine are obtained by an analytical technique. From the obtained characteristics of the machine, it is concluded that the continuous variation of

excitation with load is necessary for regulating the voltage of the machine and the excitation requirement of the machine reduces with the increase in speed. Therefore, from these results it is concluded that a SLCVC-capacitor combination for regulating the terminal voltage of the machine at rated value will be an economical proposition and may force the machine to run at its maximum capacity.

Figs 7 total reactive power needed at 1700 Watt

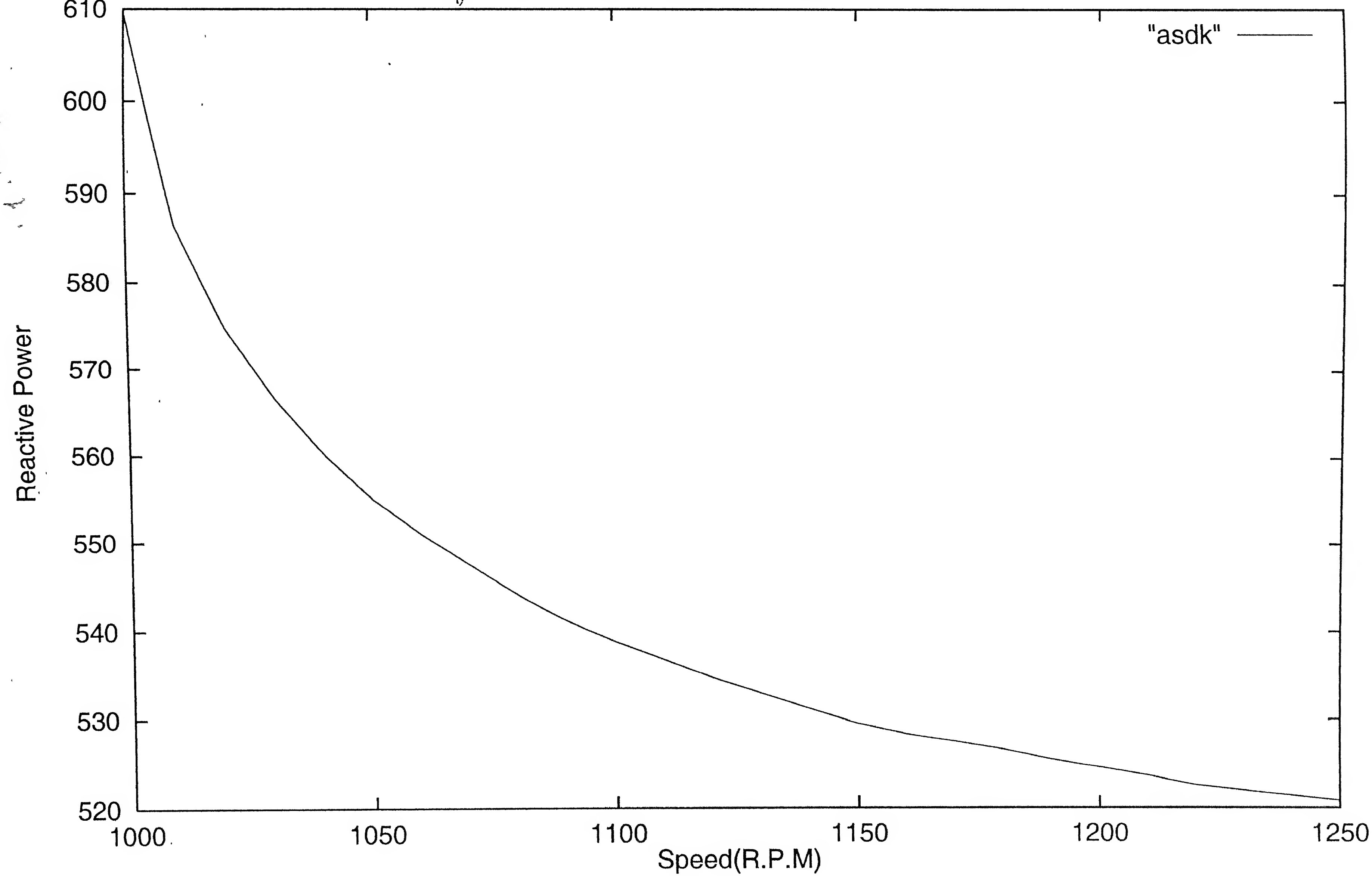


Fig.5.9 Reactive Power generated by SLCVC at 1700 Watt

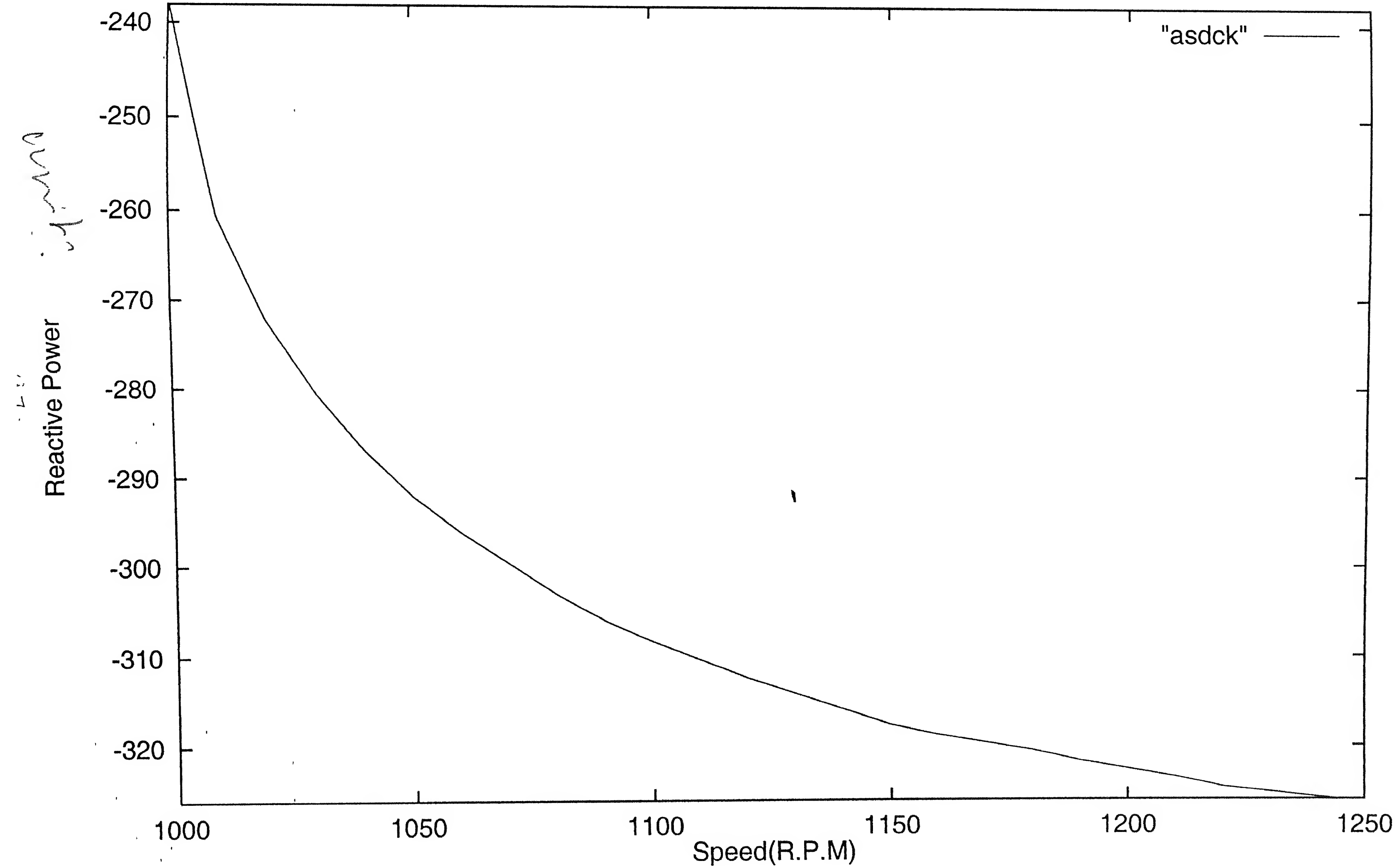


Fig 5.9 Generated frequency vs Load Power

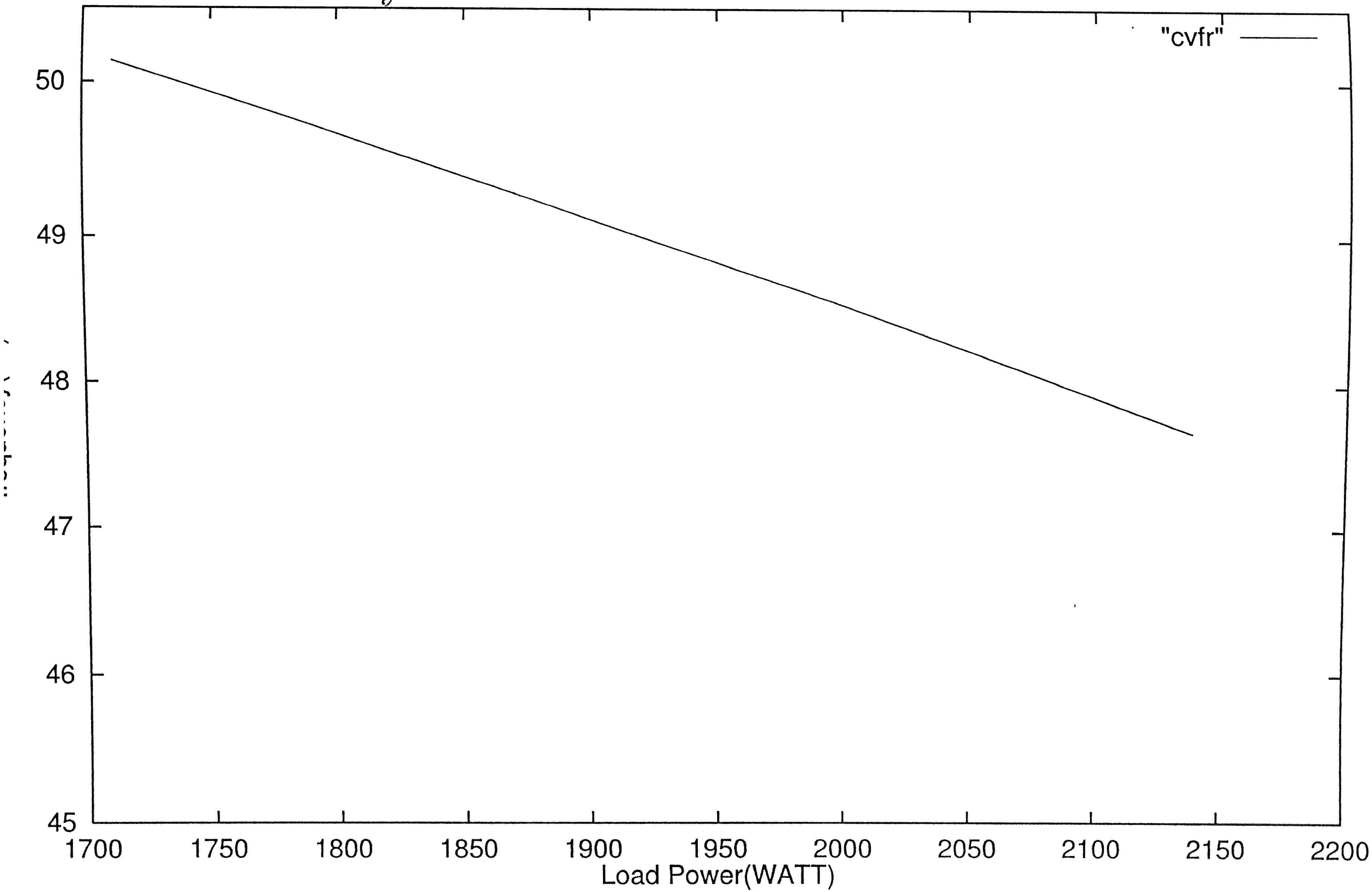


Fig. 5.10 Generated Frequency vs Power(without SLCVC)

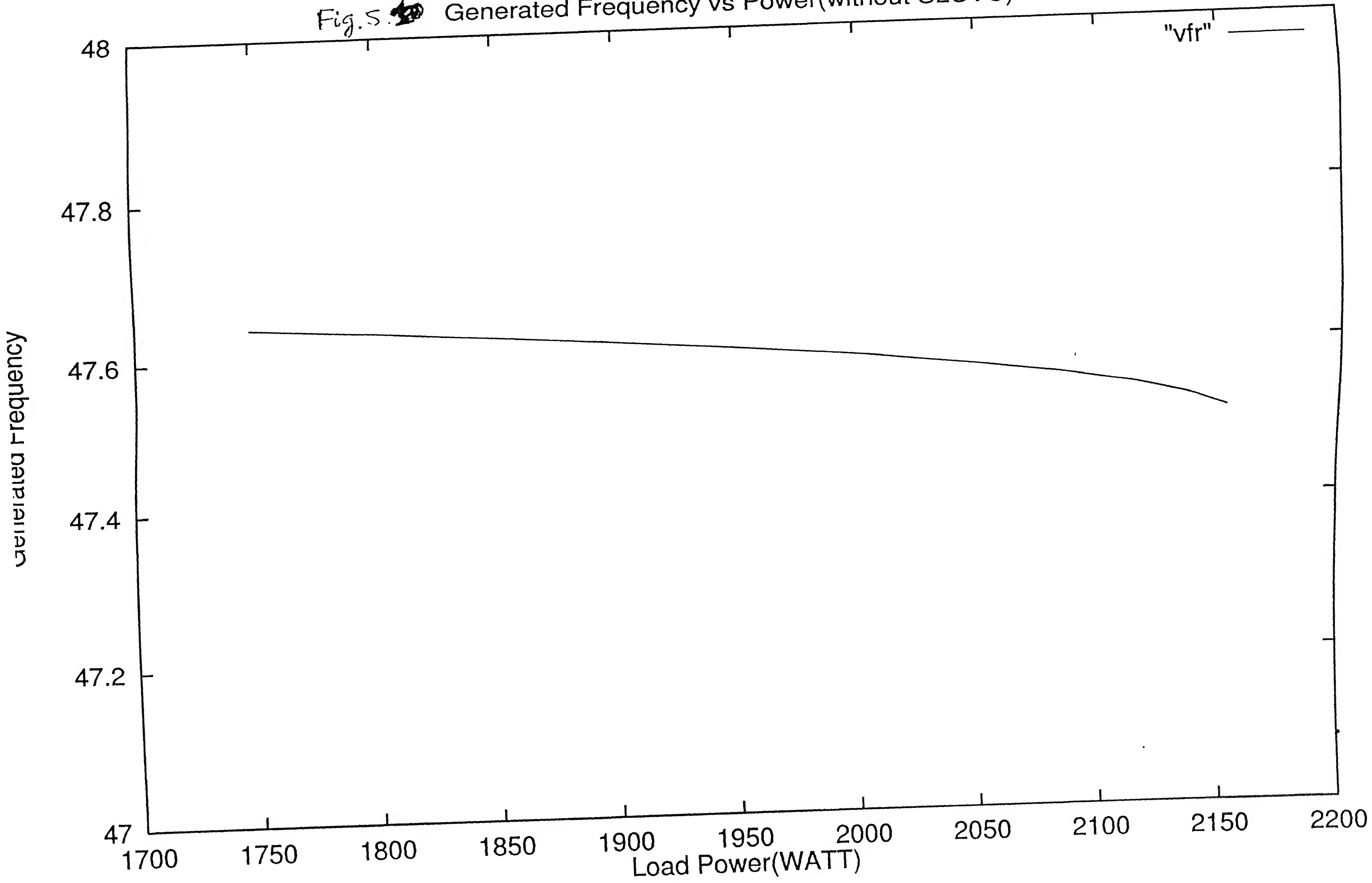
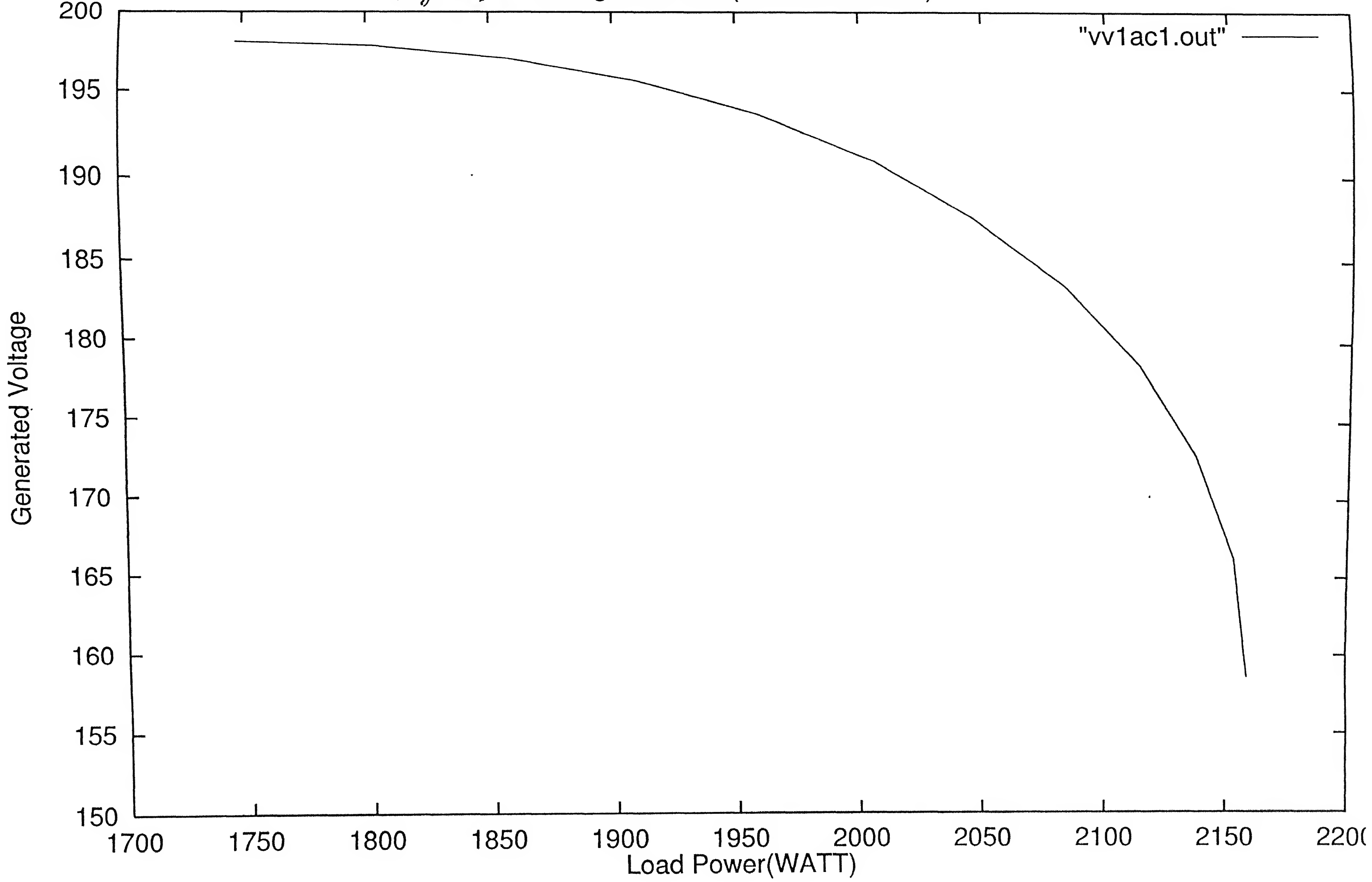


Fig. 5.11 Voltage vs Load (Without SLCVC)



CHAPTER 6

Design of Single phase Half-bridge SLCVC for single phase self-excited SEIG

6.1 Introduction

The potential of PWM self-commutated voltage source converters in the area of var compensation has been well established. These compensators offer zero power-factor operation while delivering near sinusoidal current and reduced size of output filter. With the introduction of self-commutated devices like MOSFET, IGBT and GTO etc, the PWM converter designs got simplified considerably.

The PWM self-commuted converters have two categories, viz., Voltage Source Converter and Current Source Converters. Both have the primary advantage of delivering near sinusoidal currents at zero power-factor. But CSC is slower and bulkier than VSC. Now-a-days VSC has bi-directional power transfer capability. The switching devices, such as MOSFET, used by VSC have low current ratings but high switching frequency ratings. They can serve low power applications.

This chapter presents design procedure for VSC, which uses high-frequency switching devices with diode across it. The design is done for a single-phase half-bridge VSC. A design procedure along with appropriate considerations for the selection of the converter elements is hence presented.

6.2 Basic Configuration

The basic configuration used by single-phase SLCVC is shown in fig6.1. It can conduct power in both directions. The switching devices S_1 and S_2 generate a voltage V_{an} between its two ac terminals. The voltage V_{an} has a two level wave-form for the half-bridge SLCVC. The ac terminal is directly connected to the SEIG terminal. Since the discussion to follow is restricted to low power applications, the switching devices denoted by S_1 and S_2 need to be considered as a high frequency switching device with a diode across it.

Though there are three current control techniques, viz.,

1) Hysteresis current control (HCC)
2) indirect current control
3) Predicted current control at fixed Switching frequency

HCC technique is followed here for its simplicity and also due to its suitability in low power applications.

In order to understand the design aspects of SLCVC, it is necessary to evaluate the dc link currents in the SLCVC. These are evaluated based on 'local average criterion'.

6.3DC Link Currents

Corresponding to the switching operations of the switches, the ac link current is controlled within a current window using HCC technique. The reference current is

$$i_R = I_m \sin(wt + \phi)$$

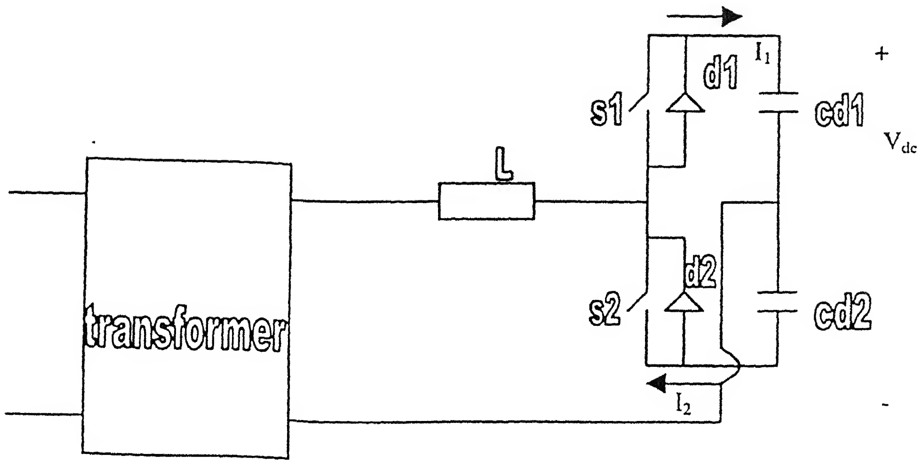


Fig.6.1Basic configuration for single-phase half-bridge SLCVC

When the current reaches the lower limit of the window, it rises to reach the upper limit of the window, while it falls to reach the lower limit of the window, when it reaches the upper limit of the window. The value I_R remains almost constant during the on-off interval as the window is considered to be very small.

The "local averages" of the on-time current I_{on} and the off-time current I_{off} are then defined as below.

$$I_{on} = \frac{\int_0^{\Delta t_1} i_R \, dt}{\Delta t_1 + \Delta t_2} \quad \text{.........} \qquad (6.1)$$

$$I_{off} = \frac{\int_0^{\Delta t_2} i_R \, dt}{\Delta t_1 + \Delta t_2} \quad \text{.........} \qquad (6.2)$$

Based on the definition of local average of currents [34], the dc link currents of the SLCVC are evaluated. These are given below.

$$i_1 = \frac{I_m}{2}\sin(wt + \phi) +$$
$$\frac{V_m I_m}{2V_{dc}}[\cos\phi - \cos(2wt + \phi)] \text{........ ....} (6.3)$$

$$i_2 = \frac{I_m}{2}\sin(wt + \phi) -$$

$$\frac{V_m I_m}{2V_{dc}}[\cos\phi - \cos(2wt + \phi)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

V_m = peak value of ac voltage

I_m = peak of the reference current

Phi = operating power factor angle selected

V_{dc} = dc link voltage

Further average ac input power

$$= \frac{V_m I_m}{2}\cos\phi \quad \ldots\ldots\ldots \quad \ldots\ldots\ldots \quad \ldots\ldots\ldots \quad \ldots\ldots\ldots \quad \ldots\ldots (6.5)$$

Equations (6.3) and (6.4) show that the dc link currents of the half-bridge SLCVC have a fundamental frequency component as well as a second harmonic component.

In general, these fundamental frequency and second harmonic components account for reactive components of current. These reactive components of the current circulate around the branches of the converter.

In should be noted that the power factor angle is near to 90 degrees during the reactive power compensation mode.

6.4Design Procedure

The design procedure is explained here in detail for the single-phase half-bridge SLCVC.

The design procedure is based on

1) finite impedance connected to the ac link. It is mainly inductive.
2) AC link current control regulated through HCC technique.
3) Switching devices assumed to be MOSFET so that low power applications can be realized.
4) An appropriate snubber circuit is to be connected across each device.

The design procedure covers the selection of the following.

1) Boost inductor L
2) Capacitor banks (C_{d1},C_{d2})
3) Switching devices (S_1,S_2)
4) Diodes (D_1,D_2)

6.4.1 Relation between the ac side and dc side voltages

Since the ac voltage V at which the SLCVC will work is known, selection of the dc voltage depends upon it. It is guided by the following criterion

$$V < \frac{V_{dc}}{2\sqrt{2}} \quad \text{..........(6.6)}$$

This criterion ensures that the diodes remain in reverse bias condition normally.

6.4.2Selection of boost inductor L

The high frequency ripple (restricted by the hysteresis window) in the ac current is generated by the fast switching of MOSFET. It is assumed that the switching frequency is quite high. The fundamental component of the ripple current has the frequency, which is same as the switching frequency and its r.m.s value is given by [34]

$$I_{1(ripple)} = \frac{4(V_{dc}/2)}{\sqrt{2}\Pi(2\Pi f_{sw}L)} \quad \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots\ldots(6.7)$$

Assuming $I_{1(ripple)}$ to be x% of the inductor r.m.s current I, the boost inductor value is given by [34]

$$L = \frac{4(V_{dc}/2).100}{\sqrt{2}\Pi(2\Pi f_{sw})I.x} \quad \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots\ldots\ldots.(6.8)$$

A more accurate alternative procedure depends upon the digital simulation. The switching frequency depends upon the hysteresis window as well as inductance. Through digital simulation of the output current, variation of switching frequency can be found out against the variation of hysteresis window size and the variation in inductance. Value of inductance can now be selected based on the desired switching frequency and current window size.

RMS current rating

The r.m.s current rating of the inductor L depends upon the maximum r.m.s current flowing through it. This is the situation when

SLCVC is consuming maximum or minimum reactive power at full loaded condition of the SEIG. The actual r.m.s current can be considered to be 1.05 times the calculated r.m.s current to account for the device power losses, wiring copper losses and wiring joint losses.

Since the inductor is on the ac side and the ripple current is quite low, the inductor can be designed with iron core. However, increase in core losses due to high frequency of the ripple current must be taken into account.

6.4.3 Selection of Capacitor banks (C_{d1}, C_{d2})

The ripple current in the capacitor bank is given by

$$i_{c1} = i_1$$

or

$$i_{c1} = \frac{I_m}{2}\sin(wt + \Phi) - \frac{V_m I_m}{2V_{dc}}\cos(2wt + \Phi) \qquad (6.9)$$

The instantaneous ripple voltage of the capacitor bank C_{d1} hence will be given by

$$\Delta v_{1(ripple)} = -\frac{1}{2C_d w}\cos(wt + \Phi) - \frac{V_m I_m}{2V_{dc}(2C_d w)}\sin(2wt + \Phi) \qquad (6.10)$$

Where w=2*3.14*f

f = supply frequency

SLCVC is consuming maximum or minimum reactive power at full loaded condition of the SEIG. The actual r.m.s current can be considered to be 1.05 times the calculated r.m.s current to account for the device power losses, wiring copper losses and wiring joint losses.

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6.4.3 Selection of Capacitor banks (C_{d1}, C_{d2})

The ripple current in the capacitor bank is given by

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The instantaneous ripple voltage of the capacitor bank C_{d1} hence will be given by

$$\Delta v_{1(ripple)} = -\frac{1}{2C_d w}\cos(wt + \Phi) - \frac{V_m I_m}{2V_{dc}(2C_d w)}\sin(2wt + \Phi) \qquad (6.10)$$

Where w=2*3.14*f

f = supply frequency

The instantaneous ripple voltage of the capacitor bank C_{d2} will be given by

$$\Delta v_{2(ripple)} = \frac{1}{2C_d w}\cos(wt+\Phi) - \frac{V_m I_m}{2V_{dc}(2C_d w)}\sin(2wt+\Phi) \qquad (6.11)$$

Thus the instantaneous ripple voltage in the output is given by

$$\Delta v_{(ripple)} = \Delta v_{1(ripple)} + \Delta v_{2(ripple)}$$

$$= -\frac{V_m I_m}{V_{dc}(2C_d w)}\sin(2wt+\phi) \qquad (6.12)$$

And the RMS ripple voltage will be

$$\Delta v_{(ripple)} = \frac{V_m I_m}{\sqrt{2}V_{dc}(2C_d w)} \qquad (6.13)$$

To restrict the voltage ripple to x% of the output dc voltage, the value of capacitor banks C_{d1} and C_{d2} ($C_{d1} = C_{d2} = C_d$) should be as given below

$$C_d \geq \frac{V_m I_m . 100}{2\sqrt{2}V_{dc}^2 . w . x} \qquad (6.14)$$

R.M.S current rating

The r.m.s currents in the capacitor bank is given by

$$I_{C(rms)} = \sqrt{[\frac{I_m}{2\sqrt{2}}]^2 + [\frac{V_m I_m}{2\sqrt{2}V_{dc}}]^2} \qquad (6.15)$$

The current rating of the capacitor bank should be greater than $I_{C(rms)}$.

Voltage rating

The dc voltage rating of the capacitor bank will depend upon the dc voltage. It is necessary to have a safety factor of at least 1.2 for the actual rated voltage of the capacitor over V_{dc} to account overcharging during transients.

6.4.4Selection of switching devices

Forward Blocking Voltage

Whenever one switch conducts, the other switch has to block the full voltage V_{dc} acting across it. Thus the forward blocking voltage rating of the switches should be greater than V_{dc}. A minimum voltage safety factor of 1.3 should be considered to account for the overcharging of capacitors.

RMS current rating

Switches conduct only for half cycle in each cycle of the input voltage. When S_2 conducts, the current through it is given by (6.4). Thus the rms current will be

$$I_{s(rms)} \approx \sqrt{[\frac{I_m / 2}{\sqrt{2}}]^2 + [\frac{V_m I_m / 2V_{dc}}{\sqrt{2}}]^2 + [\frac{V_m I_m / 2V_{dc}}{\sqrt{2}}]^2} \qquad (6.16)$$

This is the r.m.s current required to be provided by each device. Appropriate snubber circuits also help in reducing the switching losses which otherwise could be considerably higher.

Calculations of switching losses are not dealt here. However, allowance will have to be made along-with conduction losses to get the device current ratings.

Peak Current Rating

The peak current is restricted within hysteresis window. It will be given by

$$I_{s(peak)} = I_m + \frac{\Delta I_w}{2} \qquad (6.17)$$

This is the peak current, required to be provided by each device.

Minimum di/dt

Since the current transfer from diode to the switching device is almost instantaneous, the di /dt is hence given by [34]

$$[\frac{di}{dt}] = \frac{I_m}{t_{on}} \quad \ldots\ldots\ldots\ldots \quad (6.18)$$

Where t_{on} is the turn-on time of the switching device. The minimum rating should be greater than the one shown in equation (6.18).

Minimum dv /dt (forward)

Maximum rate of voltage rise dv/dt (forward) occurs at every turn on. For example, when S_2 is off and diode D_1 is conducting, the voltage across S_1 is zero. When S_2 turns on, D_1 turns off and the voltage across S_1 suddenly increases to V_{dc}. Thus S_1 has to block a forward voltage equal to V_{dc}. The change in voltage from zero to V_{dc} occurs in a finite time depending upon the turn-on time characteristics of the device.

A conservative estimate of dv/dt is hence given by

$$[\frac{dv}{dt}] = \frac{V_{dc}}{t_{on}} \quad \ldots\ldots\ldots\ldots \quad (6.19)$$

Therefore the minimum dv/dt rating of the device should be greater than the one obtained by equation(6.19).

This dv/dt could be quite high. A snubber circuit connected across the device could be so designed so as to reduce the forward dv/dt to acceptable limits. It is not, however discussed here.

6.4.5Selection of diodes

Peak inverse voltage (repeatative)

Whenever S_2 conducts, D_1 has to block the full voltage V_{dc} acting across it. Thus the peak inverse voltage rating of the diodes should be greater than V_{dc}. A minimum voltage safety factor of 1.3 may be considered to account for the overcharging of capacitor.

R.M.S current rating

Each diode conducts only for half cycle in each cycle of the input voltage. The approximate value of $I_{d(r.m.s)}$ is given by equation(6.18). This is the r.m.s current required to be provided by each diode.

Peak Current Rating

The rating is given by equation (6.19). This is the peak current, required to be provided by each diode while in working condition. The diodes are required to be of fast recovery type as the switching frequency is quite high. The reverse recovery time should be selected in such a way so as to allow the switching operation at f_{sw}. It must be noted at this stage that if MOSFETS are used as switching devices, separate diodes may not be essential as the intrinsic anti-parallel diodes of the MOSFETS may serve the purpose.

6.4.6DC Breaker Incorporation

The switching devices conduct over half-cycle alternately. If both of these accidentally conduct simultaneously, it will lead to a short-circuit on the dc bus and the semiconductor fuses (which are connected in the circuit to protect the switching devices) will have to blow to clear the fault condition. The devices will conduct simultaneously when unhealthy conditions develop. Such conditions can be due to

1) malfunctioning of the control electronics delivering gating signals to the devices.
2) Failure of the devices to withstand forward blocking voltage or dv/dt.
3) Supply voltage transients.

Generating operation is more prone to generate such fault conditions as compared to powering condition. Though the semiconductor fuses protect the devices, blowing of fuses causes considerable amount of down time of the equipment. This is undesirable in many applications. In order to overcome this problem, dc side circuit breaker is incorporated. The I^2t rating should be chosen properly from I^2t curves in fault mode. This ensures the breaker will open under the said fault condition. The breaker can be manually closed when the fault is cleared. This saves the down-time of the equipment. The fuses can now take over the function of protecting the converter against less probable faults such as earth faults or direct short-circuit on dc lines.

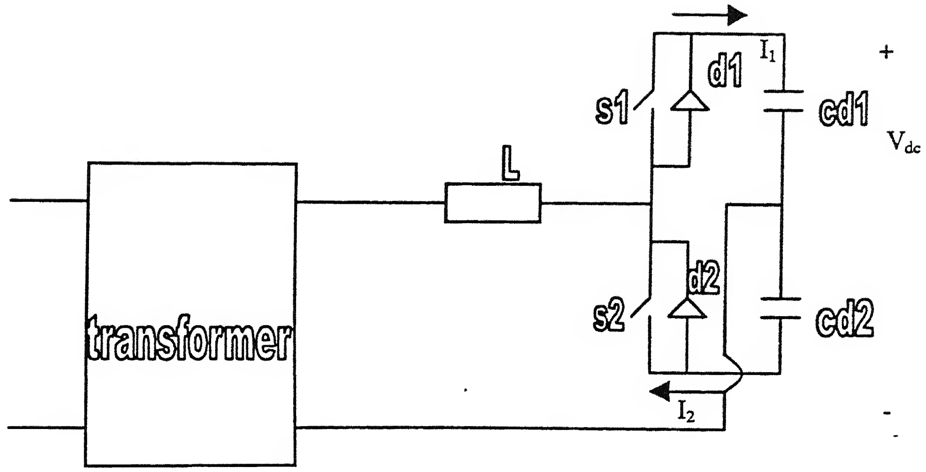


Fig.6.1Basic configuration for single-phase half-bridge SLCVC

6.5Design example

Input voltage=1Ph, 50 V, 50 Hz

Output dc voltage=100V

Input current ripple=1.0% of the boost inductor current

Switching frequency at rated load=30.0 KHz

The ratings of various components available:

---

1. **L=1.2 mH,3.53 Amp**
2. **$C_{d1}=C_{d2}=C_d$=4600 mfd,2.165 amps with dc voltage rating >120V**
3. **for s1 and s2**

   forward blocking voltage>130V

   r.m.s current rating >2 amps

   peak current rating >5 amps

   minimum di/dt rating> 10 amps/microseconds(assuming turn-on time=0.5 microseconds)

minimum dv/dt rating> 200V/microseconds

R.M.S and peak current ratings here are the currents, which the device should be able to deliver when mounted on a heat-sink and the given ambient specification.

4. For d1 and d2

   forward blocking voltage>130V

   r.m.s current rating >2 amps

   peak current rating >5 amps

   RMS and peak current ratings here are the currents, which the device should be able to deliver when mounted on heat-sink and the given ambient specification.

5. for transformer at ac link

   200 V/50 V, 200 VA

   Leakage reactance =4.4 mH

6.6 Determination of the maximum swing of angle delta

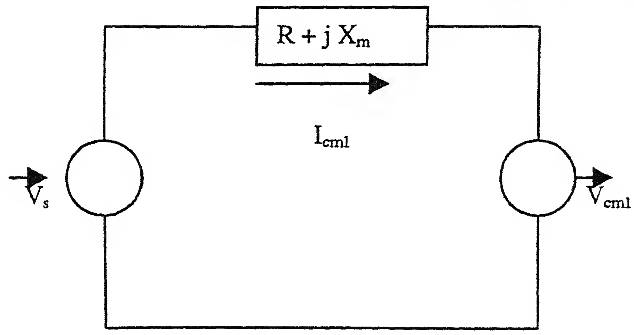


Fig. 6.2: Single line diagram of the compensator connected to utility

6.6.1 Basic Theory

From fig 6.2, fundamental component of current drawn by the main compensator is given by

$$I_{cm1} = \frac{V_s - V_{cm1}\angle -\delta}{Z\angle\theta} \quad \text{...(6.23)}$$

Where delta = angle by which V_{cm1} is lagging V_s

$Z = R + j\,w\,L_m$
R = overall loss component of the system

$$\theta = \tan^{-1}\left(\frac{wL}{R}\right)$$

therefore

$$I_{cml} = ((V_s - kV_{dc}\cos\delta) + jKV_{dc}\sin\delta)/Z\angle\theta \quad \text{.......................................(6.24)}$$

Where k is the M.I of the main compensator.

On simplification,

$$|I_{cm1}| = \sqrt{\frac{I^2_{cm1p(real)}}{2} + \frac{I^2_{cm1p(quadrature)}}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.25)$$

$$I_{cm1p(real)} = \sqrt{2}\frac{\sqrt{(V_s - kV_{dc}\cos\delta)^2 + (kV_{dc}\sin\delta)^2}}{Z}$$

$$\times \cos[\tan^{-1}\{\frac{kV_{dc}\sin\delta}{V_s - kV_{dc}\cos\delta}\} - \theta] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.26)$$

$$I_{cm1p(quadrature)} = \sqrt{2}\frac{\sqrt{(V_s - kV_{dc}\cos\delta)^2 + (kV_{dc}\sin\delta)^2}}{Z}$$

$$\times \sin[\tan^{-1}\{\frac{kV_{dc}\sin\delta}{V_s - kV_{dc}\cos\delta}\} - \theta] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.27)$$

Where delta is the angle by which V_L lags V_s

6.6.2 Calculation

Here L = 5.6mH

$I_{C(rms)}$ = 4.08 amps

V_s = 100V

M.I of the compensator=0.5(=V_l/V_{dc})

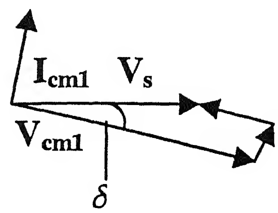
The highest value of the delta angle swing = 8.23 degrees.

(When SLCVC is consuming or generating maximum reactive power)

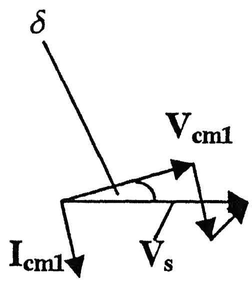
6.7 Conclusion

Due to its simple construction, design and capability to work in zero power-factor condition, SLCVC is likely to gain a major percentage

share in the industrial applications as var compensator. An insight in the design procedure and considerations, hence, was felt essential and timely. The design procedure covered here with example should help the design engineer to build up some control scheme.



(a)



(b)

Fig.6.3: Phasor Diagram of the Realistic SLCVC

CHAPTER 7

Conclusion

7.1. Conclusions

Static Reactive Power Compensation by utilizing the state of the art concept of Synchronous Link Converter Var Compensators (SLCVC) for SEIG, have become a major thrust area of research. New topologies and control techniques are being proposed to enhance the performance of such systems. When a SEIG is used in a stand-alone power system, the system complexities dominate its overall function. Such a system needs an excitation source that is capable of releasing and absorbing the reactive current in order to regulate the terminal voltage with changing load under steady-state and transient conditions. There is a good scope of using SLCVC as voltage regulator for a power system of SEIG as it is possible to operate in capacitive as well as in inductive mode without using ac capacitor or inductor except an electrolytic capacitor in the dc bus.

The SLCVC based voltage regulator provided to the SEIG a desirable feature of synchronous converter operating in inductive and capacitive modes. The use of SLCVC helps the SEIG to save from de-excitation during the severe condition of load change. It has a faster dynamic response for regulating the voltage. The voltage-regulating scheme is adaptive to the changing load condition and hence it is possible to

operate the SEIG at almost constant voltage at a wide range of load variation.

As the proposed solid-state regulator is capable of generating both the capacitive as well as inductive current, the large ac capacitor and inductor banks with their associated switchgear and protection, used in conventional SVCs, are not needed. This results in a significant reduction in size and makes it applicable in isolated power system at remote places.

There is an advantage of improved dynamic performance and the reliability of the SEIG scheme with the proposed voltage regulator . The implementation of the SLCVC based voltage regulator in the SEIG system, will reinforces the technology of small power generation from non-conventional sources of energy.

The performance characteristics of the machine in both single phase and three-phase cases are obtained by an analytical technique. From the obtained characteristics of the machine, it is concluded that the continuous variation of excitation with load is necessary for regulating the voltage of the machine and the reactive power requirement of the machine reduces with speed. Therefore, from these results it is concluded that an SLCVC-capacitor combination for regulating the terminal voltage of the machine at rated value will be useful and may force the machine to run at its maximum capacity.

7.2.Scope for further Work

1. The dissertation deals with a reactive power compensation scheme for a stand-alone three-phase SEIG. Application of the same control technique with suitable modifications for a single-phase SEIG can be a potential research area.
2. Study of the engineering considerations involved in scaling up the proposed scheme for actual power level.
3. System studies of the proposed technique in connection with a practical case.
4. Although the technique of steady-state analysis of SEIG is effective for performance prediction, they require lengthy and tedious task of deriving the coefficients of the simultaneous equations or high degree polynomials. So there is a need to develop a general but yet simple technique that can be applied to different configurations of three-phase and single-phase SEIG with different kind of loads, such that minimal mathematical complexities are involved whenever a new configuration is taken up to study.

APPENDIX A

The [L], [G] and [R] matrices are given below:

$$[L]=\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}$$

$$[R]=\begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix}$$

$$[G]=\begin{bmatrix} 0 & -w_r L_s & 0 & -w_r L_m \\ w_r L_s & 0 & w_r L_m & 0 \\ 0 & -\dfrac{(w-w_r)}{w_r} & 0 & -\dfrac{(w-w_r)}{w_r} \\ \dfrac{(w-w_r)}{w_r} & 0 & \dfrac{(w-w_r)}{w_r} & 0 \end{bmatrix}$$

APPENDIX B

A 3-phase cage induction motor is selected for computation. The electrical details and the parameters of the machine are as below.

Line voltage-415V

Rating-3.7kw

Stator connection – star

Frequency-50Hz

Pole-4

Rated speed=1500R.P.M

R_s=0.053p.u

R_r=0.061p.u

L_s=0.01280H

L_r=0.01160H

L_{mr}=0.1895H

J=5 kg-m^2

K_1=1.6275

K_2=0.0105

The parameters of the 3-ph SLCVC system are as below

R_f=0.5ohm

L_f=20mH

C=53.44microFarad

The proportional and integral constants of the dc bus PI controller are 0.37 and 6.0 respectively.

The corresponding values for the ac side PI controller are 0.14 and 4.5 respectively.

C_{dc}=400microfarad

Hb=0.08amps

APPENDIX C

The ratings and parameters of the single-phase induction generator are given below:

Voltage rating-220V

Power rating-2.5kw

Rated speed -1000r.p.m

R_1=1.47ohm

R_2=2.57ohm

X_1=4.15ohm

X_2=4.15ohm

X_{mr}=60.4ohm

K_1=332.95

K_2=2.2727

Appendix D

Fourth-order Runge-Kutta Methods

The most popular RK methods are fourth order. There are an infinite number of versions. The following is sometimes called the classical fourth-order RK method:

$$y_{i+1} = y_i + [\frac{k_1 + 2k_2 + 2k_3 + k_4}{6}]h$$

Where,

$$k_1 = f(t_i, y_i)$$

$$k_2 = f(t_i + \frac{h}{2}, y_i + \frac{hk_1}{2})$$

$$k_3 = f(t_i + \frac{h}{2}, y_i + \frac{hk_2}{2})$$

$$k_4 = f(t_i + h, y_i + hk_3)$$

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